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Compendium

Space Tug Systems Study (Storable)

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Presented to;
George C. Marshall
Space Flight Center

MARTIN MARIETTA

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Volume 2 | Final Report | January 1974

COMPENDIUM

SPACE TUG SYSTEMS STUDY (STORABLE)

Presented to:

George C. Marshall
Space Flight Center

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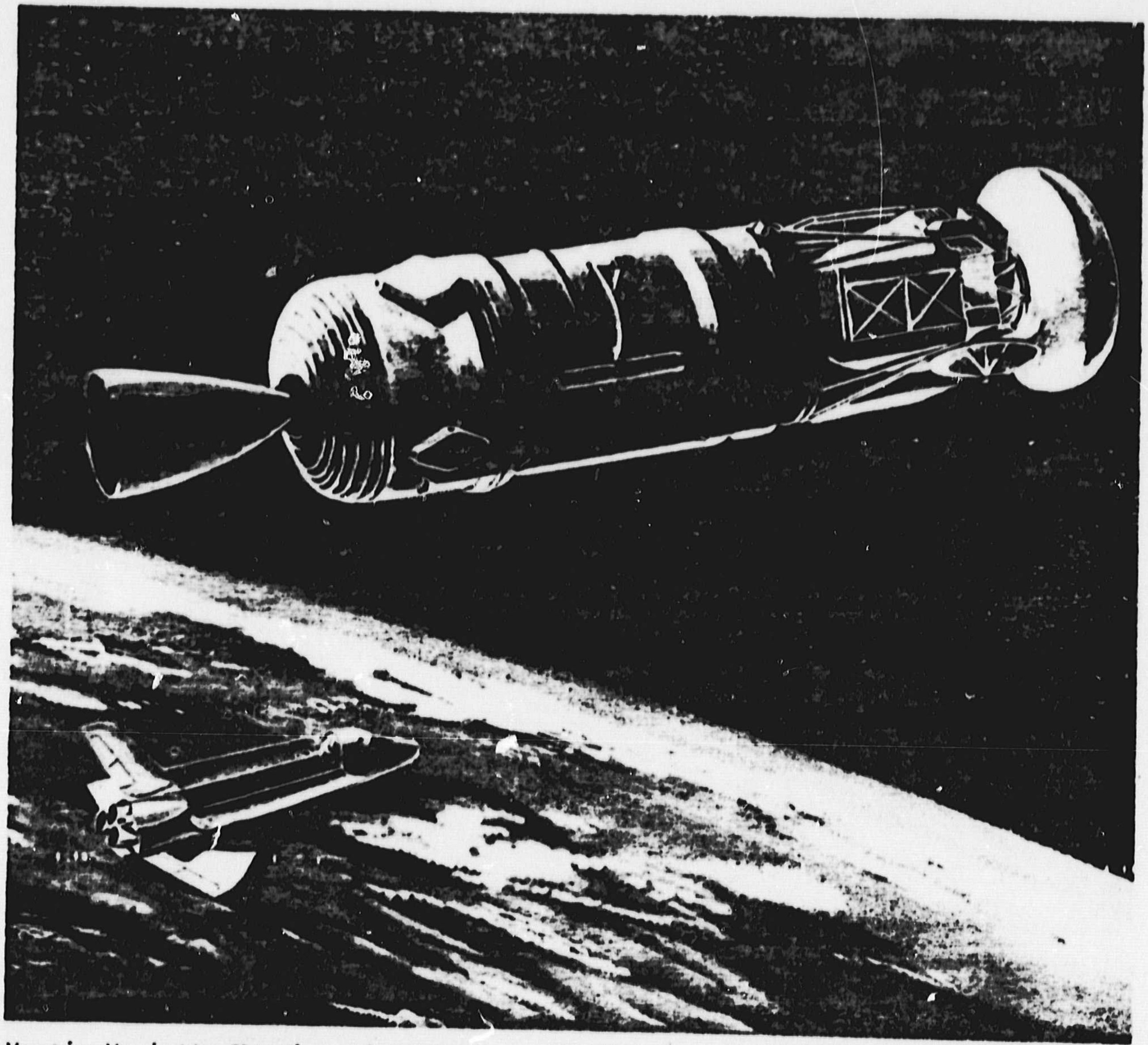

Martin Marietta Version of Space Tug (Storable) with Spacecraft

FOREWORD

This final report is submitted in accordance with the requirements of Data Requirement MA-03 of the Data Procurement Document of contract NAS8-29675, as clarified by NASA letter No. PD-TUG-C-73-207 dated October 26, 1973, signed by Robert J. Davies, Study Manager.

This final report is submitted in three separate volumes:

Volume 1 - Overview Presentation

Volume 2 - Compendium

Volume 3 - Executive Summary

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1.0 INTRODUCTION

The Space Transportation System (STS) includes an upper stage or Space Tug to perform higher-energy missions than are possible with the Orbiter alone. The Tug will be carried to low Earth orbit in the Orbiter payload bay. The Tug will separate from the Orbiter and go to various other orbits to deliver, inspect, service, and/or retrieve a spacecraft; it will also be used for planetary missions. This upper stage is envisioned as a high-performance reusable machine with a high level of reliability, safety, and autonomy. The Tug offers economic benefits that augment the basic capabilities of the STS.

National budget constraints impose limits on early funding available for Tug development. Evaluation of various Tug options is therefore necessary for selection of the most cost-effective development plan without sacrificing potential economic benefits during the STS operational phase. This study was initiated to evaluate possible storable-propellant Tug configurations and program plans consistent with the above constraints. In the broadest sense, there are four program alternatives for the Space Tug:

1) Use of existing expendable stages modified for use with Shuttle, followed by a Space Tug at a later date;

2) Use of a modified growth version of existing expendable stages for greater performance and potential reuse, followed by a Space Tug at a later date;

3) Use of a low-development-cost, reusable, interim Space Tug available at Shuttle initial operational capability (IOC) that could be evolved to greater system capabilities at a later date;

4) Use a direct-developed Tug with maximum potential to be available at some specified time after Space Shuttle IOC.

The Space Tug Systems Study (Storable) considered program alternatives 3) and 4) using Tug configurations with Earth-storable propellants. Many variations, or "capability options," of these alternatives were considered. During the study, the capability options were narrowed down to three final options for detailed program definition.

- <u>Final Option 1</u> - An interim Tug that would provide payload delivery (but not retrieval) capability at or about Shuttle IOC;

- <u>Final Option 2</u> - A direct-developed Tug that would provide payload delivery and retrieval capability approximately four years after Shuttle IOC;

- Final Option 3 - A phase-developed Tug that would provide delivery capability at or about Shuttle IOC, and retrieval and increased performance capability approximately four years later.

The final option definitions were evaluated in depth, including subsystem characteristics, vehicle configuration, weight and performance, mission capture, ground operations, flight operations, ground support equipment, facilities, safety, programmatics, and cost. Results of the final option definitions were presented in the *Selected Option Data Dump* (Ref 5.8).

Study results are presented in Ref 5.1 through 5.11. This report summarizes these results and is baselined to the September data dump; results of subsequent analyses are presented as deltas or "Additional Analysis."

1.1 GOALS AND OBJECTIVES

The objective of this study was to systematically analyze program elements for storable propellant Tugs—progressively adding depth to the definition of these options that met user requirements in the most cost-effective manner.

1.1.1 Overall Study Goals

The goal of the study was to select the options that best satisfied the following key issues:

1) Provide maximum performance capability within physical, operational, programmatic, and other constraints;

2) Provide a high level of safety and reliability;

3) Minimize development costs;

4) Minimize production and operational costs through reusability;

5) Define selected configurations and programmatics that minimize STS costs, provide reasonable yearly funding requirements, and minimize program risks.

1.1.2 Specific Objectives

The specific objectives for the study tasks presented in Section 1.3 are:

1) Task 1 - Evaluate mission requirements to define program and system requirements. Determine whether candidate conceptual designs meet mission requirements.

2) Task 2 - Collect, analyze, and evaluate data for potential subsystems, components, and propellant options.

3) Task 3 - Synthesize Space Tug vehicle concepts from selected subsystem options.

4) Task 4 - Provide programmatics and cost data to support evaluation of subsystems, vehicle configurations, and final option definitions. Programmatics includes schedules, test planning, manufacturing plans, logistic support, ground and flight operations, and GSE and facility assessment.

5) Task 5 - Define the Final Options selected in depth, including design, performance capability, programmatics, and cost. Perform sensitivity studies to determine the impact of ground rules and assumptions used.

1.2 GUIDELINES

The principal guidelines used for the study are presented in the *Data Package, Space Tug Systems Study* (Ref 5.12) and the *Space Shuttle System Payload Accommodations* document, (Ref 5.13). Additional study inputs are presented in Ref 5.14 through 5.41. Significant ground rules and assumptions used or evolved during this study are:

- The Orbiter park orbit will be 160 n mi (296 km) in all cases. The Tug will return for Orbiter rendezvous to 170 n mi (315 km) orbit.

- Tug payloads to be retrieved will be passive and designed for retrieval by the Tug.

- During the Orbiter/Tug terminal rendezvous, the Tug will be passive cooperative. Normally, the Orbiter will perform the terminal rendezvous, docking, and retrieval in the acquisition of the Tug.

- Contaminants from the Tug (including the ACPS thrusters) will not impinge harmfully on the spacecraft or the Orbiter.

- The Tug will be designed to be returned to Earth in the Orbiter and be reused; reusability with minimum maintenance/ground-turnaround time is a design objective.

- The Tug will permit monitoring of critical parameters/functions by the Orbiter at all times while in the cargo bay or in the vicinity of the Orbiter.

- The Space Tug will use Earth storables as main-engine propellants.

- The mission completion reliability goal for the Tug shall be 0.97 minimum for all mission phases. Levels of redundancy will be selected and defined to meet this criterion.

- The Tug design goal will be to provide sufficient protection to assure an 0.995 probability of no mission failures due to meteoroid penetration for each mission.

- The Space Tug will be sized in accordance with Orbiter payload capabilities and mission requirements. Specifically, the total gross weight of the Tug, spacecraft, and supporting equipment will not exceed 65,000 lb (29,484 kg); the Tug and supporting equipment will not exceed 35 ft (10.7 m) in length.

- As a goal, no single Tug failure will result in a hazard that jeopardizes the flight or ground crews. No single Tug failure will result in unprogrammed motion of the Tug while in the vicinity of the Orbiter. Also:

1) The design of the main propulsion system will be fail safe.

2) The design of the ACPS will be fail-operational/fail-safe.

3) The design of the critical command and control circuitry will be fail-operational/fail-safe as a minimum.

- All primary and secondary structural components, where critical load conditions occur while the Space Tug is attached to the Orbiter, will be designed to an ultimate factor of safety of 1.4 and a yield factor of safety of 1.1. For a structural component whose critical load condition occurs when failure of the component will have no effect on the Space Shuttle System, the component will be designed to an ultimate factor of safety of 1.25 and a yield factor of safety of 1.1. This includes the main propellant tanks for both internal pressure and externally applied loads. The proof pressure for the main propellant tanks is determined from the greater of : (a) 1.05 x limit design pressure, or (b) a pressure determined from a fracture mechanics analysis, sufficiently high to verify service life. All high-pressure vessels will be designed to an ultimate factor of safety of 2.0, with proof pressure determined from the greater of: (a) 1.5 x limit pressure, or (b) a pressure, determined from a fracture mechanics analysis, sufficiently high to verify service life.

- The Tug evolutionary changes will be made in such a way as to minimize spacecraft requalification and interface changes; the basic Tug structure will not be involved.

- The communication system will be compatible with available NASA and DOD ground and space networks.

- The Tug design for abort will be for normal landing loads, but with tanks full. For crash loads, the design will be with tanks empty and with sufficient structural integrity to preclude failure but allow permanent deformation.

- For calculating Tug configuration dry weights, a 10% contingency factor is applied to the total stage weight.

- The Tug will be designed for propellant loading off-site in a vertical position with provisions for vertical or horizontal unloading.

- The Tug will be designed for vertical or horizontal loading/unloading of the Tug into or out of the Orbiter, with or without spacecraft, and propellant tanks empty or full.

- The Tug will have the capability of changeout with/without spacecraft in ten hours and be capable of launch from ready standby within two hours.

- For programmatic considerations, the number of Tug flights will be limited to three in 1980 and 21 in 1981, due to Shuttle availability. For programs with an IOC of 1981 or later, a reasonable two-year buildup will be determined. Tug reliability losses are assumed to be one per hundred flights, each loss will result in an additional flight.

1.3 STUDY PLAN

Figure 1-1 is a logic flow diagram for the study, with the nomenclature used throughout this report; applicable paragraph numbers are shown. The study consists of five basic tasks:

1) Task 1: Mission Analysis

2) Task 2: Subsystem Analysis

3) Task 3: Configuration Concepts

4) Task 4: Supporting Programmatics and Costing Analysis

5) Task 5: Program Definition.

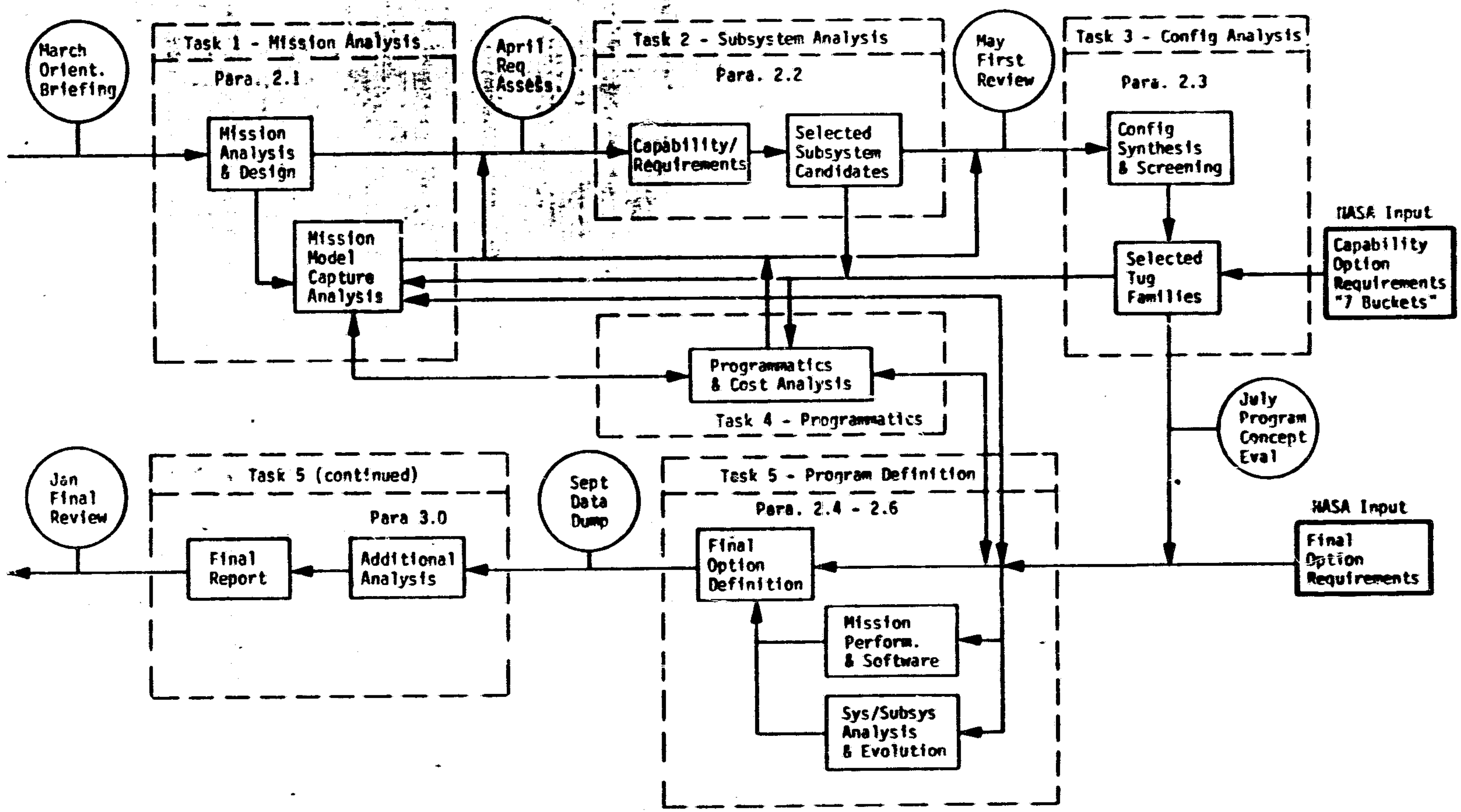

Fig. 1-1 Study Flow Diagram

Significant study milestones were:

1) March 7, 1973 - Orientation Briefing (Ref 5.2)

2) April 11, 1973 - Requirements Assessment (Ref 5.3)

3) May 30, 1973 - First Review (Ref 5.4)

4) July 19, 1973 - Program Concept Evaluation (Ref 5.5)

5) September 17, 1973 - Selected Option Data Dump (Ref 5.8)

6) January 1974 - Final Review.

1.3.1 Mission Analysis (Task 1)

This task outlined the overall Tug mission requirements and objectives, supported the selection of subsystems and systems meeting these requirements, and provided a detailed mission accomplishment analysis of selected configurations and programs.

Overall mission requirements were derived from NASA-supplied mission models and other data. Results of this task are presented in paragraph 2.1.

1.3.2 Subsystem Analysis (Task 2)

The first part of this task (capability/requirements) was concerned with determining subsystem functional requirements, taking into consideration the time-phased mission requirements and potential subsystem combinations making up candidate Tug configurations. The first part of this task was also concerned with collecting data on candidate subsystems and components and assessing their capabilities and limitations. The second part of the task consisted of evaluating alternatives and selecting subsystem candidates to be used in the synthesis of the various Tug configurations. The resulting "selected subsystem candidates" were presented at the First Review on May 30, 1973 (Ref 5.4).

The subsystem analysis continued throughout Tasks 3 and 5: The selected subsystem candidates were used in the configuration synthesis and screening in Task 3, from which Tug families were selected as described in paragraph 1.3.3. The final option definitions evolving from Task 3 were used in the program definition discussed in paragraph 1.3.5.

Descriptions of subsystem candidates and how they evolved throughout the study are presented in Section 2.2.

1.3.3 Configuration Concepts (Task 3)

Selected subsystem candidates resulting from Task 2 were used to synthesize various Tug configurations. Candidate Tug configurations were screened against previously developed criteria and "Tug families" were selected for each of seven capability options referred to as "buckets". The capability options are defined in paragraph 2.3. Concurrent with the definition of Tug families, the operations, supporting equipment, and interfaces were defined.

Results of this task were presented at the Program Concept Evaluation (Ref 5.5). Details were presented in paragraph 2.3 of this report.

Three final options were selected for definition in Task 5. A single-stage configuration and a stage-and-a-half configuration were identified for definition in one of these three final options.

1.3.4 Supporting Programmatics and Costing Analysis (Task 4)

This task provided the necessary programmatic data in the form of project schedules, programmatic analyses, test planning, manufacturing analyses, and cost analyses to support evaluation of the selected subsystem candidates, selected Tug families, and final option definitions (Tasks 2, 3, and 5). This task also identified and analyzed facility and logistic support requirements and the repair and refurbishment modes.

1.3.5 Program Definition (Task 5)

Final options selected from Task 3 are identified in Table 1.3-1. These were analyzed in depth in Task 5. Subsystems were defined to WBS Level 6, including subsystem characteristics, installation and supporting systems. Tug inboard profiles were prepared, and Tug mass properties were determined. From these data, Tug performance capability was calculated and mission capture analysis was completed. The mission capture analysis was used to determine launch rates, ground support requirements, and crew sizes, which were reflected in operational costs. Detailed schedules were prepared for each final option and costs estimated to WBS Level 6. Sensitivity studies were also conducted, as shown in Table 1.3-2.

Results of this task were presented at the *Selected Option Data Dump* (Ref 5.8). Details are presented in paragraphs 2.4 through 2.6 of this report.

Study results and detailed supporting data are baselined to the *Selected Option Data Dump*. Additional analyses and subsequent deltas to these results are presented in paragraph 3.0 of this report.

Table 1.3-1 *Summary of Final Option Definitions*

	Final Option 1	Final Option 2		Final Option 3			Final Option 3A		
Development	Direct	Direct		Phased			Phased		
Stages	Single	Single		Single			Stage-and-A-Half		
Configuration	Interim	Delivery	Retrieval	Initial Delivery	Final Delivery	Final Retrieval	Initial Delivery	Final Delivery	Final Retrieval
IOC (DEC)	1979	1983		1979	1983		1979	1983	
Dry Weight	2,886 lb (1309 kg)	2,750 lb (1247 kg)	3,982 lb (1353 kg)	2,934 lb (1331 kg)	Same as Option 2 Delivery	Same as Option 2 Retrieval	4,004 lb (1816 kg)	3,820 lb (1733 kg)	4,043 lb (1834 kg)
Length	27 ft 2 in. (8.28 m)	26 ft 11 in. (8.204 m)		27 ft 9 in. (8.458 m)			22 ft 11 in. (6.985 m)	22 ft 1 in. (6.731 m)	22 ft 1 in. (6.731 m)
Propellant Weight	56,700 lb (25,719 kg)	59,800 lb (27,125 kg)		59,800 lb (27,125 kg)			59,800 lb (27,125 kg)		
Payload Capability* Delivery	3,800 lb (1724 kg)	6,000 lb (2722 kg)	4,900 lb (2223 kg)	4,400 lb (1996 kg)			4,900 lb (2223 kg)	6,500 lb (2948 kg)	5,300 lb (2404 kg)
Retrieval	--	--	1,800 lb (816.5 kg)	--			--	--	1,900 lb (862 kg)
Propulsion	Low P_c OME	Class I		High P_c OME					
Avionics	FSI, Current IMU	FSI, Lightweight IMU, Laser Radar for Retrieval		Same as Option 1					
Power	Battery	Solar Array							
Structure	Isolated Titanium Tanks; Titanium, Aluminum, & Composite Body Structure						Same as Options 1, 2, & 3 plus Aluminum Drop Tanks		
Thermal	Passive Paint; MLI each end; Base Heatshield								

*Payload capability to geostationary orbit

Table 1.3-2 Task 5 Sensitivity Studies

A.	SPECIFIC TASK 5 SENSITIVITY STUDIES
	1. Impact of providing power to the payload
	2. Autonomy sensitivity study
	3. 0.97 reliability sensitivity study
	4. 30-day servicing mission
	5. Impact of DOD communications requirement
	6. Impact of payload command, control, and checkout requirement
	7. Structural design-life sensitivity study
	8. Impact of deploying/retrieving a spin-stabilized payload
	9. Impact of rendezvous and docking
B.	PROGRAM OPTION SENSITIVITY STUDIES
	1. Sensitivity study on main engines
	2. IOC sensitivity studies - each Final Option
	3. Impact of DOD programmatics - each Final Option
	4. Tug off-loaded sensitivity study
	5. Additional payload capture potential

1.4 KEY ISSUES

The following key issues are indicated by the Overall study goals:

1) Provide maximum performance capability within physical, operational, programmatic, and other constraints;

2) Provide a high level of safety and reliability;

3) Minimize development costs;

4) Minimize production and operational costs through reusability;

5) Define selected configurations and programmatics that minimize STS costs; provide reasonable yearly funding requirements and minimize program risks.

These key issues have been addressed in a logical and systematic manner, as shown in the study plan (paragraph 1.3). Results are summarized in the following paragraphs.

1.4.1 Provide Maximum Performance Capability within Physical, Operational, and Programmatic Constraints

A standardized mission model was developed that challenged the ability to provide maximum performance capability within the guidelines presented in paragraph 1.2. Maximum performance capability was achieved through the trade studies and system optimization in Subsystem Analyses (Task 2), Configuration Concepts (Task 3), and Program Definition (Task 5). For example, the avionics subsystem selected uses a flexible signal interface (FSI) concept, which provides maximum capability, flexibility, and reliability with minimum weight.

The resulting geostationary performance capability is shown in Table 1.3-1 for the final option definitions. Table 1.4-1 presents a summary of the mission accomplishment based on 100% capture. Details are presented in paragraph 2.1. Multiple spacecraft delivery minimizes the number of flights required; Tug length is as important as delivery capability in minimizing the number of flights. A "delayed retrieval" mode is used to retrieve spacecraft that exceed the capability of a single Tug.

Delayed retrieval is defined by the following types of flights:

1) Type A - Delivery and Deorbit for Delayed Retrieval - This is a combined delivery and deorbit flight of a Tug to geostationary orbit. The Tug delivers one or two spacecraft to geostationary orbit, then rendezvous and docks with a spacecraft to be retrieved, than performs a deorbit burn and releases the spacecraft into an intermediate orbit for later "delayed retrieval flight" as described in 3) below.

2) Type B - Dedicated Deorbit for Delayed Retrieval - This is the flight of a Tug to geostationary orbit where it rendezvous and docks with a spacecraft to be retrieved, then performs a deorbit burn and releases the spacecraft into an intermediate orbit for a later "delayed retrieval flight" as described in 3) below.

3) Type C - Delayed Retrieval Flight - This is the flight of a Tug to an intermediate orbit (not geostationary) where it retrieves a spacecraft previously deorbited from a geostationary orbit by an earlier Tug flight.

Table 1.4-1 Summary of Mission Accomplishment (100% Capture)

	Final Option			
	1	2	3	3A
<u>Spacecraft Delivered</u>				
NASA	201	136	201	201
DOD	159	122	186	186
Total	360	258	387	387
<u>Spacecraft Retrieved</u>				
NASA	-	90	87	87
DOD	-	89	84	84
Total	-	179	171	171
Total Spacecraft	360	437	558	558
<u>Delivery Flights</u>				
NASA	124	75	115	107
DOD	114	39	80	79
Total	238	114	195	186
<u>Retrieval Flights</u>				
NASA	-	90	87	87
DOD	-	89	84	84
Total	-	179	171	171
Total Flights	238	293	366	357

Table 1.4-2 presents a breakdown of the retrieval flights, including the types of delayed retrieval described above.

The sensitivity studies conducted in Task 5 revealed the following effects on the performance capability of the final options.

1) Providing power to the spacecraft has a significant effect on the performance of a battery-powered Tug and drives the design to a solar-array system.

2) Level I autonomy has a significant effect on performance. Other levels of autonomy do not. (Autonomy Level II was baselined.)

3) Safety and reliability requirements (which affect performance) are equal drivers.

4) The storable Tug can readily perform a 30-day servicing mission.

5) Requirements for DOD communications, payload command control and checkout, and spin/despin of the spacecraft do not have a signif-effect on performance capability.

6) Rendezvous and docking has a significant effect on delivery capability if delivery and retrieval are performed on the same flight.

1.4.2 Safety and Reliability

Safety and reliability were considered to be key issues throughout this study. Safety reviews insured that every Tug candidate was a safe and effective element of the Space Transportation System. Fail-operational/fail-safe requirements were met without exception. Because safety requirements dictated subsystem redundancy in many places, achievement of reliability requirements was insured. Sensitivity studies indicate that reliability and safety are equal drivers.

Emphasis was placed on component selection and redundancy in the subsystems so that all candidates met or exceeded safety and reliability requirements. Reliability for the final option definitions is discussed in paragraph 2.4; safety is discussed in paragraph 2.5.1.

1.4.3 Minimum DDT&E Costs

Components, subsystems, and systems were selected to minimize development costs. In general, near-state-of-the-art technology was used so that performance increases could be achieved with minimum DDT&E costs. A substantial list of supporting research and technology (SRT) was identified that would precede the development phase to reduce program risk.

Table 1.4-2 Breakdown of Retrieval Flights (100% Capture)

Item	Option		
	2	3	3A
Maximum retrieval requirement (geostationary)	3500 lb (1588 kg)	2200 lb (998 kg)	2200 lb (998 kg)
Retrieval capability (geostationary)	1800 lb (816 kg)	1800 lb (816 kg)	1900 lb (862 kg)
Spacecraft requiring retrieval	179	171	171
Flights required for 100% capture	225	208	208
Round-trip flights (deliver & retrieve same type of spacecraft)	77	77	76
Unequal round-trip flights (deliver & retrieve different types of spacecraft)	16	18	17
Retrieval flights (retrieval with no delivery)	40	39	41
Delivery & deorbit for delayed retrieval (Type A)	43	34	35
Dedicated deorbit for delayed retrieval (Type B)	3*	3*	2*
Delayed retrieval flight (Type C)	46	37	37

*These flights were dedicated deorbit flights because no spacecraft existed in these years that required delivery.

DDT&E costs for the final selected options as presented in the *Selected Option Data Dump* (Ref 5.8) are presented in Table 1.4-3. The cost of the first Tug, which carries an operational payload, is included. Kick-stage (Space Tug auxiliary stage) costs are also included.

Additional Analysis (para 3.6) shows that the DDT&E costs can be reduced considerably by revising certain ground rules and assumptions.

1.4.4 Minimum Production and Operations Costs through Reusability

The reusability of the final option definitions provides for minimum production and operations costs. For example, Final Option 3 requires only 16 Tugs and 9 kick stages to accomplish 352 flights. This includes four reliability losses (one loss per hundred flights) and eight Tugs, which are expended on high-energy planetary missions.

Table 1.4-4 presents fleet size and operational data for each final option. The number of flights differs from that shown in Table 1.4-1 because the number of flights has been limited in the first two years of operations and reliability losses have been added. (See *Guidelines*, (para 1.2.) The stage-and-a-half configuration (Final Option 3A) suffers from lack of reusability due to the large number of drop tanks expended.

Tables 1.4-5 and 1.4-6 present production and operating costs, respectively, for the final option definitions presented in the *Selected Option Data Dump* (Ref 5.8). Additional analysis (para 3.6) shows that production and operating costs can be reduced considerably by revising certain ground rules and assumptions used.

1.4.5 Programmatics and Transportation Costs

Table 1.4-7 summarizes total transportation costs for each final option definition as presented in the *Selected Option Data Dump* (Ref 5.8). The phased-development program (Final Option 3) returns the most benefits (in terms of the number of missions achieved) for the cost expenditure. The stage-and-a-half (Final Option 3A) requires fewer flights for mission model capture, but the Shuttle cost savings are more than offset by the higher Tug costs.

IOC sensitivity studies indicate that stretching out the development time can reduce annual peak funding requirements, although this increases total DDT&E costs slightly. Peak funding should be a key factor in choosing the optimum program for the Tug.

Sensitivity studies also show that use of the DOD programmatic approach reduces risk, but delays production, producing an uneven distribution in annual funding requirements. It is therefore recommended that commit-to-production not be contingent on flight test evaluation.

Table 1.4-3 Development Cost Breakdown

WBS	Identification	Final Option, $M			
		1	2	3	3A
01	Project Management	15.2	15.9	17.3	19.5
02	Systems Engineering	22.0	27.7	29.1	31.1
03	Tug Vehicle Main Stage	85.9	140.8	181.1	192.0
04	Tug Vehicle Auxiliary Stage	26.1	18.1	26.1	26.1
05	Logistics	2.4	2.6	2.9	3.1
06	Facilities	19.6	19.6	19.6	19.6
07	GSE	23.4	26.2	27.6	29.0
08	Vehicle Test	40.8	45.4	47.3	57.4
11	Flight Operations - DOD	0.3	0.3	1.0	1.0
12	Flight Operations - NASA	1.1	1.1	1.7	1.7
	Total	236.8	297.7	353.7	380.5

Table 1.4-4 Production and Operations Data

	Final Option			
	1	2	3	3A
Launch Operations (Years)	11	7	11	11
Crew Size - ETR	96	142	142	156
- WTR	48	86	86	100
- Central Support	10	14	12	14
- Total	154	242	240	270
Number of Flights* - NASA	119	139	196	189
- DOD	108	115	156	155
- Total	227	254	352	344
Expendables - Tugs (Main Stage)	10	6	8	8
- Kick Stage 10	3	5	5	5
- Kick Stage 1.5	4	-	-	-
- Kick Stage 10/1.5	4	-	4	4
- Drop Tanks	-	-	-	292
Fleet Size - Tugs (Main Stage)	15	13	16	16
*Includes reliability losses & limited flights in first two years	3	3	4	4

Table 1.4-5 Production Cost Breakdown

WBS	Identification	Final Option, $M			
		1	2	3	3A
01	Project Management	7.8	8.0	9.8	11.0
02	Systems Engineering	13.7	14.7	17.9	18.0
03	Tug Vehicle Main Stage	99.6	104.6	126.5	300.9
S3	Spares, Tug Vehicle Main Stage	3.5	4.4	4.9	5.2
04	Tug Vehicle Auxiliary Stage	19.1	7.2	18.2	18.1
S4	Spares, Tug Vehicle Auxiliary Stage	0.7	0.4	0.4	0.4
05	Logistics	1.8	1.8	1.9	1.9
07	GSE	19.5	27.6	29.3	32.0
11	Flight Operations - DOD	0.1	0.1	0.1	0.1
12	Flight Operations - NASA	0.3	0.3	0.3	0.4
	Total	166.1	169.1	209.3	388.0

Table 1.4-6 Operations Cost Breakdown

WBS	Identification	Final Option, $M			
		1	2	3	3A
01	Project Management	20.8	13.2	20.0	20.2
02	Systems Engineering	45.6	36.2	49.3	50.3
S3	Spares, Tug Vehicle Main Stage	13.9	17.4	19.6	20.9
S4	Spares, Tug Vehicle Auxiliary Stage	1.7	1.5	1.7	1.7
05	Logistics	5.8	4.7	6.2	6.2
06	Facilities	4.1	3.8	3.9	3.9
07	GSE	7.8	6.5	8.5	8.5
09	Launch Operations - WTR	12.0	16.6	19.7	20.9
10	Launch Operations - ETR	25.5	25.5	38.4	41.2
11	Flight Operations - DOD	13.7	13.2	16.9	17.9
12	Flight Operations - NASA	17.2	15.5	22.3	23.6
13	Refurbishment & Integration - WTR	24.2	29.9	36.5	36.5
14	Refurbishment & Integration - ETR	49.7	49.7	75.3	75.0
	Total	242.0	233.7	318.3	326.8

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Table 1.4-7 *Cost Summary for Final Option Definitions (Selected Option Data Dump)*

	Final Option, $M			
	1	2	3	3A
Tug Costs				
SRT	(12.2)	(19.8)	(19.8)	(20.0)
DDT&E	237	298	354	381
Production	166	169	209	388
Operations	242	234	318	327
Total	645	701	881	1,096
Number of Flights	227	254	352	344
Average Operations Cost per Flight	1.07	0.92	0.90	0.95
Shuttle Costs	2,384	2,667	3,696	3,612
Transportation Cost	3,029	3,368	4,577	4,708

Table 1.4-8 Cost Summary for Revised Option Definitions

	Final Option, $M			
	1	2	3	3A
Tug Costs				
SRT	(12.2)	(19.8)	(19.8)	(20.0)
DDT&E	183	254	263	286
Production	158	153	190	361
Operations	224	208	256	261
Total	565	615	709	908
Number of Flights	227	254	336	331
Average Operations Cost per Flight	0.99	0.82	0.76	0.79
Shuttle Costs	2,384	2,667	3,528	3,476
Transportation Cost	2,949	3,282	4,237	4,384

Additional studies (para 3.0) indicate that the engine should not be phased in Final Option 3 and that the IOC date for ETR should be delayed until December 1980 to reduce early peak-year funding. A build-up in launch rate and crew size should be provided at ETR and WTR, rather than drive the program directly to 100% capture. Additional cost savings items are presented in paragraph 3.6. The resulting revised costs are presented in Table 1.4-8. Because all Tugs (interim, cryogenic, or storable) require kick stages, which are not well defined, DDT&E costs for kick stages have been omitted from Table 1.4-8 for ease of comparison; production and operational costs for the kick stages are included.

Programmatics and costs are discussed in paragraph 2.4 for each final option definition presented at the *Selected Option Data Dump* (Ref 5.8). Paragraph 2.5 presents backup data for safety, ground operations, flight operations, and interfaces. Paragraph 2.6 discusses the supporting research and technology (SRT) program that would precede the development phase. Paragraph 3.0 summarizes the results of additional studies conducted since the *Selected Option Data Dump* (Ref 5.8).

2.0 SYNOPSES OF ANALYSES

2.1 MISSION REQUIREMENTS ANALYSIS

The mission requirements analysis was initiated by deriving Tug design requirements and operational program requirements from a representative NASA/DOD mission model. The sequence of activity included:

- Delineation of gross functional requirements;

- Identification and evaluation of candidate staging and flight techniques for meeting these gross requirements;

- Identification of subsystem requirements derivable from mission considerations;

- Evaluation of the ability of candidate Tug elements to perform model missions;

- Derivation of annual flight schedules associated with selected Tug program options capturing the NASA/DOD mission model.

Gross functional requirements for the Tug system were discussed in some detail at the Requirements Assessment Meeting (Ref 5.3), and were expanded as the study progressed. The mission model that has evolved shows a preponderance of geostationary missions, significant numbers of polar and midinclination Earth orbits, and a small array of Earth-escape missions. Table 2.1-1 shows the distribution of these missions. Spacecraft retrieval is an important aspect of NASA/DOD desires--service missions and sortie missions are significant considerations. In the most general terms, to accomplish these missions, the Tug must be able to:

- Deliver a spacecraft and return to the vicinity of the Shuttle Orbiter;

- Rendezvous with an orbiting spacecraft and return it to the vicinity of the Shuttle Orbiter;

- Operate away from the Shuttle Orbiter for up to six days;

- Achieve spacecraft/energy goals associated with the specified mission model.

Certain variations in goals have been explored, e.g., delivery-only capability with shorter mission duration and reduced spacecraft objectives, mission durations as long as 30 days, Tug operation in autonomous modes, etc.

Table 2.1-1 Mission Distribution

Spacecraft	Final Options			
	1	2	3	3A
Geostationary	182	207	264	264
Midinclination & Planetary	106	133	180	180
Polar	72	97	114	114
Totals	360	437	558	558

Identification and evaluation of Tug staging methods and associated flight techniques has been an important part of the study. The candidates investigated in detail include:

- Single-stage reusable Tug;
- Reusable Tug core stage with expendable drop tanks (referred to as stage and a half);
- Two-stage reusable Tug;
- Expendable upper Tug stage (kick stage) used with the preceding options.

Various flight techniques appropriate to these staging methods have been evolved during the study and are reported in various states of development throughout the study documentation. The most significant conclusions about the top-level Tug configuration selection defined by the staging method selected are:

- The single-stage Tug operating with expendable kick stages for planetary missions and in the delayed retrieval mode for heavy geostationary spacecraft offers one of the simplest most desirable approaches to mission model capture (preferred approach).
- The stage-and-a-half Tug operated in the same mission modes offers increased capability--but at a significant increase in vehicle complexity and program cost.
- The two-stage Tug requires the use of a more complex flight technique (trapeze mode) to achieve significant improvement in retrieval capability over the single-stage Tug. This retrieval capability improvement is not believed to justify the complexity of the trapeze mode.

The staging/flight technique approach has a dominant effect on most Tug subsystem requirements, resulting subsystem design, and the ability of the developed configuration to capture selected missions. These results, in turn, establish the programmatic aspects of any approach to Tug design, development, and operation. The following subsections summarize study results in the mission-design/mission-capture areas and indicate where more detailed information can be found.

2.1.1 Mission Design

2.1.1.1 Critical Mission Requirements - This study has developed preliminary designs and associated programmatics for achieving two discrete levels of Tug capability. The schedule of this achievement has been a variable, but is not pertinent to this discussion. The *basic* Tug requirement is to achieve all spacecraft delivery and retrieval goals defined by the NASA/DOD mission model, subject to constraints imposed by Shuttle design and particular spacecraft service requirements. An *interim* goal, selected to minimize Tug development cost and risk, has also been defined. This interim goal deletes retrieval requirements, long-duration missions, and servicing spacecraft with electrical power. These are the key requirements that can be reduced to ease the difficulty of Tug development.

Table 2.1-2 is an overview of Tug top-level requirements. A more detailed expansion at system and subsystem levels is available in Vol 5.0 of the *Selected Option Data Dump* (Ref 5.8). The three basic sources of Tug requirements are those imposed by mission objectives, the spacecraft, and the Shuttle. Of the array of mission objectives, the desired autonomy level and ground-control requirement merit special mention. During the study, four levels of autonomy were identified. These are described in detail in paragraph 2.5.3.2 and show a range from complete ground control to Tug operation that is completely independent of any external stimulus. Basic designs evolved during the study are consistent with Autonomy Level II, in which no ground command or dedicated ground systems are required for Tug flight (although they can use undedicated ground-based RF radiation). The basic concept of ground control evolved from the Tug has been to provide a complete capability to back up Tug flight functions from the ground--but to use it only for contingencies. Thus, Tug mission success can be enhanced in situations in which ground intervention is acceptable, but the level of autonomy need not be compromised in those cases in which it is of consequence.

Two spacecraft-imposed requirements have proved to be of particular consequence to Tug system design. The first is limitation of the g level imposed on spacecraft to approximately 3.6 g. This has required the use of new kick-stage solid motors based on slow-burning propellants to keep axial accelerations down when carrying light- to medium-weight spacecraft. The second is the requirement for the Tug to provide spacecraft with 300 W during Tug/spacecraft flight. For the Interim Tug, this requirement was waived and required mission duration was shortened to make an inexpensive battery-powered Tug feasible.

Table 2.1-2 Top-Level Tug Design Requirements

Requirement Category	Basic Requirement	Interim Tug Variance
Mission-Derived Requirements		
Operating Regime	Near Earth [<100,000 n mi (185,200 km)] Thermal, Radiation, Meteoroid Environment	
Transportation Mode	Deliver & Retrieve Spacecraft	Deliver S/C & Return Empty
Mission Endurance	6 Days (28-Day Goal)	36 hr
Subsystem Operating Limits	See Vol 5.0 (Ref 5.8)	
Mission Reliability	0.97	
Autonomy Level	Level II Provided (Std)	
Ground Control	Provide Complete Backup	
S/C-Derived Requirements		
Power to Spacecraft	300 W (during Tug flight)	No Power Required
S/C Data Handling	16 kbps from S/C, 2 kbps to S/C	
Acceleration Limitation	3.6 g max axial	
Placement Accuracy	Geostat Spec,NASA *Data Package* (Ref 5.12)	
Attitude Constraints	Not Specified	
Shuttle-Derived Requirements		
Safety	Fail-Operate/Fail-Safe in Vicinity of Shuttle	
Acceleration Loads	*Payload Accommodations* (Ref 5.13)	
Return Accuracy	Shuttle Maneuver Limits Spec by JSC, Req Assess. Mtg	
Abort Propellant Dump	Full Propellant Dump Desired [min to 32,000-lb (14,515-kg) Tug/spacecraft]	

Shuttle-imposed requirements have an extremely significant effect on Tug design. Manned safety considerations including fail-operational/fail-safe requirement are the driving influences on the level of redundancy required, particularly in the case of the attitude-control system (avionics and propulsion). Orbiter-imposed landing loads are a critical consideration in the structural design. Abort propellant dump is a key issue in the Orbiter/Tug fluid interface, and the central issue in guidance and navigation is the ability to return within the specified Orbiter retrieval envelope. This has been the most severe requirement driving navigation update requirements.

2.1.1.2 Vehicle Staging Trades - Three basic Tug staging arrangements were considered (Table 2.1-3). Each of these is discussed in detail in Vol 6.0 of the *Selected Option Data Dump* (Ref 5.8). A single-stage arrangement is the most desirable from the point of view of operational simplicity and low development cost. The stage-and-a-half candidate (using expendable drop tanks) offers improved performance in exchange for only partial reusability and a more complex configuration. The two-stage approach offers enhanced retrieval capability when used in the more complex trapeze flight mode. The two-stage penalty lies largely in the need to buy more stages, and in the more complex logistics and operations associated with them. Each of these basic staging approaches can be supported, when necessary, with expendable kick stages to ease the burden of high energy requirements on the reusable mode.

Table 2.1-3 Configuration/Technique Candidates

Stage Arrangement \ Mission Category	Low-Energy Earth Orbital (incl polar)	High-Energy Earth Orbital (incl geostationary)	Near-Planetary Deep Space
Single Stage	Basic 1-Stage*	Basic 1-Stage* Kick Stage Delayed Retrieval*	Basic 1-Stage* Kick Stage* Expendable*
1½-Stage	Core Stage Only*	Basic 1½ Stage* Kick Stage Delayed Retrieval*	Basic 1½-Stage* Kick Stage* Expendable*
2-Stage	One Stage Only*	Slingshot Staging* Trapeze Staging* Kick Stage	Slingshot Staging Trapeze Staging Kick Stage* Expendable Upper Stage*
*Selected techniques.			

The single-stage Tug configuration used in its basic reusable mode can be applied to all the basic types of missions shown in Table 2.1-3. It has more than adequate performance for many low-energy Earth-orbital missions, resulting in a considerable capability for multiple missions. A basic geostationary capability up to 6000 lb (2722 kg) delivery, 1800 lb (816.5 kg) retrieval was achieved by our advanced configurations. This is adequate to meet all Earth-orbital delivery requirements, but requires enhancement for retrieval. Kick stages were found to be of limited value for retrieval enhancement.

A delayed retrieval mode was found to be a completely satisfactory approach. This technique is discussed later in paragraph 2.1.1.3.4. Some near-planetary missions can be achieved by the single-stage vehicle used alone in the reusable mode. Many of the higher-energy planetary missions require the use of a kick stage; some require expending the single-stage Tug. All these techniques are reflected in the capture analysis.

The stage-and-a-half arrangement is used for target missions in the same manner as the single stage, with two exceptions. The most obvious is that the stage-and-a-half incorporates drop tanks, which supply propellants for initial mission phases and are then discarded. The other exception is that the core-only vehicle without drop tanks can capture a significant portion of the low-energy missions. These factors have been incorporated in the capture analysis and associated program cost estimates developed during the study.

The two-stage arrangement offers a wide variety of possible flight techniques, and makes its assessment a more elaborate task than the preceding cases. For low-energy missions, one stage flown alone is attractive because it offers the possibility of an alternative use for the remaining Orbiter cargo-bay volume and weight. The alternative use aspect has not been quantitatively addressed in this study. Sling-shot and trapeze flight techniques have been considered for higher-energy missions (e.g., geostationary). These are defined as:

1) Sling-shot mode - Lower Tug stage delivers upper stage part way on its mission—both stages return independently to Shuttle Orbiter;

2) Trapeze mode - Lower Tug stage delivers upper stage part way on its mission—lower stage retrieves and returns upper stage to Shuttle Orbiter after upper stage has completed its mission.

The sling-shot mode does not produce performance equal to the large single-stage vehicle, due to the fixed weights (engine, avionics) that each of the two stages must carry. It is preferred for missions in which performance is adequate due to operational simplicity--note that all geostationary delivery missions fall in this category. The trapeze mode enhancement of retrieval capability is particularly significant, more than doubling the geostationary retrieval spacecraft weight, as shown on page 84 of the *Program Concept Evaluation* (Ref 5.5). The operational price of this improvement is development of two integrated stage missions and a stage-to-stage rendezvous before the mission can be completed. The planetary picture parallels the other options; kick stages and expending the Tug are still required options. The expended stage is a smaller stage, but indications are that it is not much cheaper than the alternatives.

Comparison of these techniques was made on the basis of performance capability, overall cost to perform defined spacecraft programs, development cost, and operational complexity. Net conclusions about staging arrangement that these studies evolved are:

1) The one-stage Tug is the most desirable arrangement;

2) The two-stage Tug is the least desirable;

3) Stage-and-a-half advantages are outweighed by the disadvantages;

4) Kick stages are a valuable and necessary part of the reusable storable Tug picture (but only required for high-energy planetary missions).

2.1.1.3 <u>Flight Technique</u> - The flight technique analysis had two purposes:

(1) Establish energy requirements for selected configuration/mission combinations;

(2) Establish functional requirements that the Tug system/subsystems must meet.

This effort has been reported at all study review sessions; the final results are summarized in Vol 6.0, Sect. I of the *Selected Option Data Dump* (Ref 5.8).

2.1.1.3.1 <u>Standard Geostationary Flight Technique</u> - The geostationary mission poses problems that are, in most respects, typical of high-energy Earth-orbital missions. The Tug must ascend to a phase-specified location in the mission orbit, perform specified orbit operations (e.g., spacecraft separation, multiple placement, rendezvous), descend, and phase with the waiting Shuttle Orbiter. Figure 2.1-1 summarizes the resulting mission profile. Associated timelines are given in Vol 6.0, Sect. I of the *Selected Option Data Dump* (Ref 5.8). Ascent phasing requirements are established by the desired placement longitude--and control the time that the Tug remains with the Shuttle before starting the ascent phasing burn and the size of the ascent phasing orbit. The variation in mission duration due to placement longitude is 12 hours. The nature of on-orbit operation is a strong mission determinant. A rendezvous sequence taxes auxiliary propulsion and terminal navigation systems, while phasing two spacecraft to different locations can extend mission duration to the limit. Shuttle return phasing establishes the size of the descent phasing orbit. Note that Shuttle Orbiter nodal regression compensation of this mission is obtained simply by adjusting the timing of the deorbit burn. There is no energy budget associated with this correction--a situation that is not true for nonequatorial mission orbits.

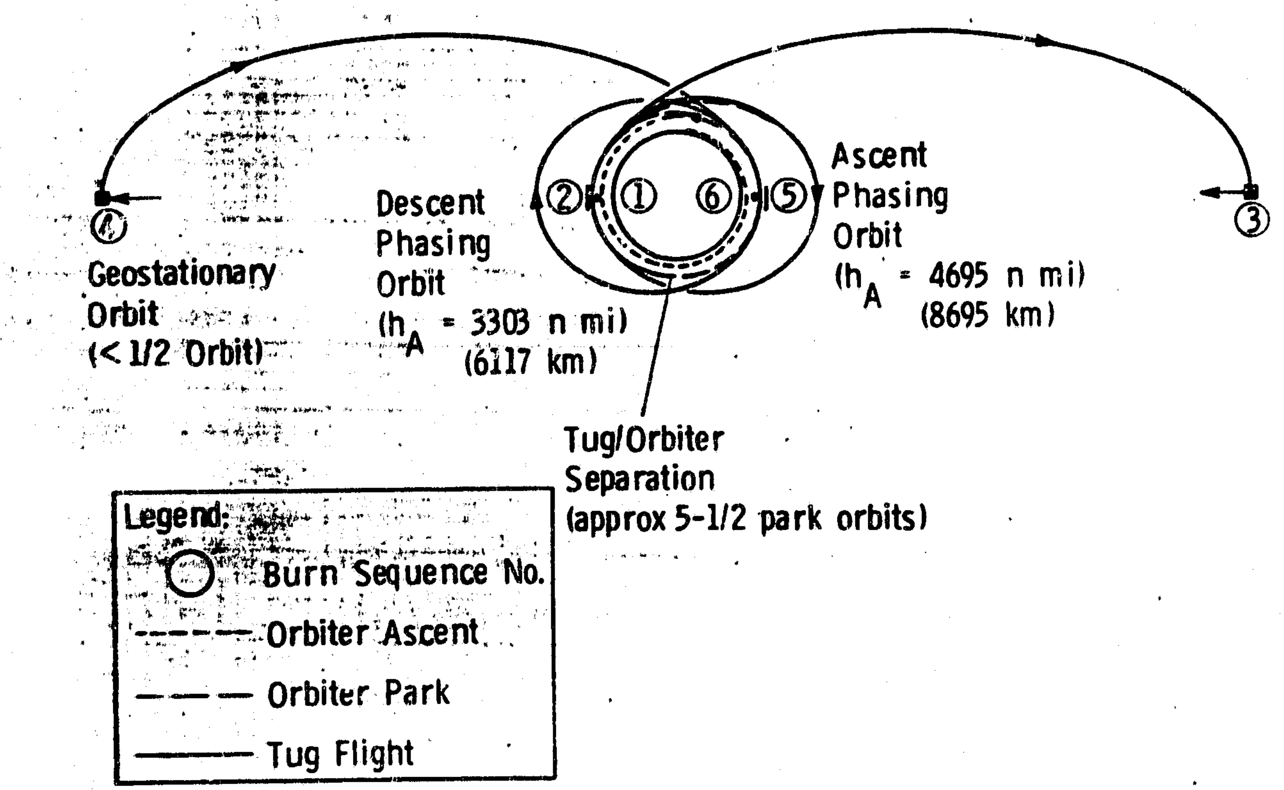

Fig. 2.1-1 Geostationary Mission Profile

2.1.1.3.2 Guidance and Navigation Accuracy Considerations - The critical guidance and navigation requirement for the Tug is to achieve the Shuttle Orbiter retrieval envelope at the end of its mission. Overall dimensions of this envelope were established at ±15 n mi (27.8 km) altitude, ±0.15° (2.6×10^{-3} rad) inclination, and ±60 n mi (111.1 km) downrange (3σ). This requirement is more stringent than the geostationary-mission delivery-accuracy specification and demands the ability to update the Tug's basic inertial measurement unit. Updates based on ground track and on several on-board sensors were considered during the study. Figure 2.1-2 illustrates the performance of three on-board sensor systems on a geostationary ascent transfer. The horizon scanner (HS) approach yields the poorest performance, but offers the potential of Autonomy Level I. The one-way Doppler (OWD) and interferometer landmark tracker (ILT) systems show nearly equal performance. The OWD, which is consistent with Autonomy Level II, was selected for Tug. This system yields Shuttle return accuracy well within the retrieval envelope identified, as shown in Table 10-5, Vol 6.0, Sect. I of the *Selected Option Data Dump* (Ref 5.8).

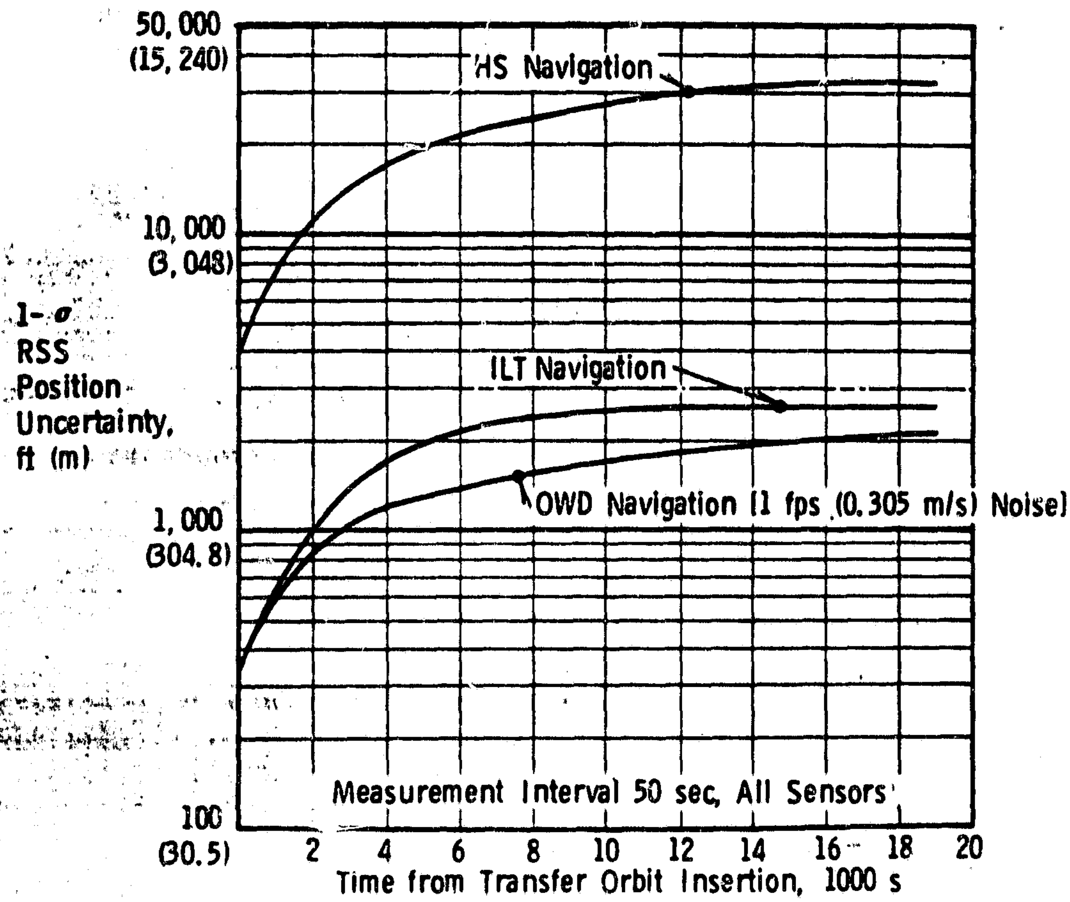

Fig. 2.1-2 Geostationary Transfer Orbit Uncertainty

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2.1.1.3.3 Trapeze Staging - One of the major reasons for not pursuing the two-stage configuration throughout the study was the operational complexity of flight techniques that make it a superior performer. The two-stage configuration offers a wide variety of interesting flight techniques, but perhaps the most critical to Tug is the use of trapeze staging to enhance geostationary retrieval capability. This technique is illustrated in Fig. 2.1-3. The lower Tug stage carries the upper stage part way on its mission, waits in an intermediate orbit while the upper stage retrieves a spacecraft and returns to the intermediate orbit, and then returns the upper stage/spacecraft to the Shuttle Orbiter. An additional nodal correction maneuver is required, which becomes larger as mission duration increases. As long as mission duration can be kept to a minimum (12 hours in geostationary orbit), this technique offers the highest geostationary retrieval capability of any Shuttle mission technique investigated. This advantage is overcome by several disadvantages, including: (1) the extra Tug/Tug rendezvous, (2) the need to design two intertwined Tug missions, and (3) the basic expense of maintaining a Tug fleet with more stages in it. Even though they are smaller, they are nearly as expensive as the large single stage. Based on these considerations, the two-stage Tug was not carried throughout the study.

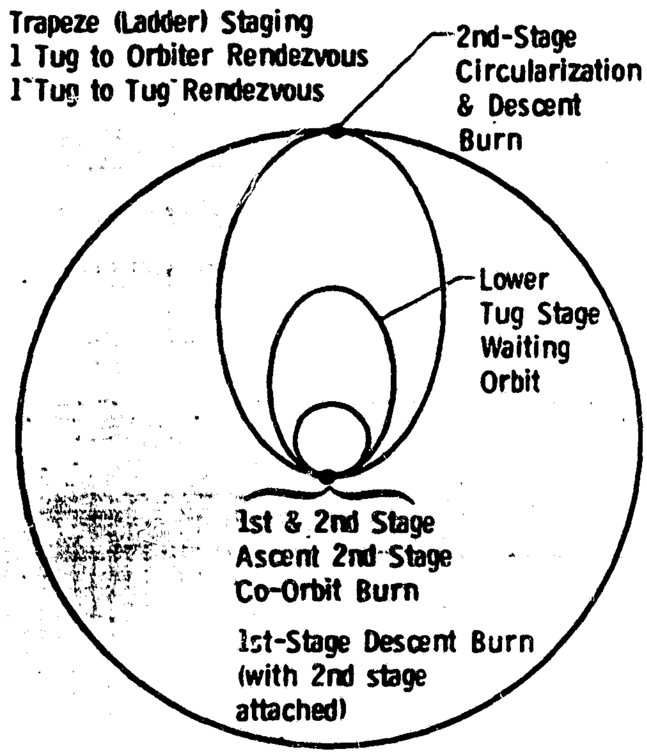
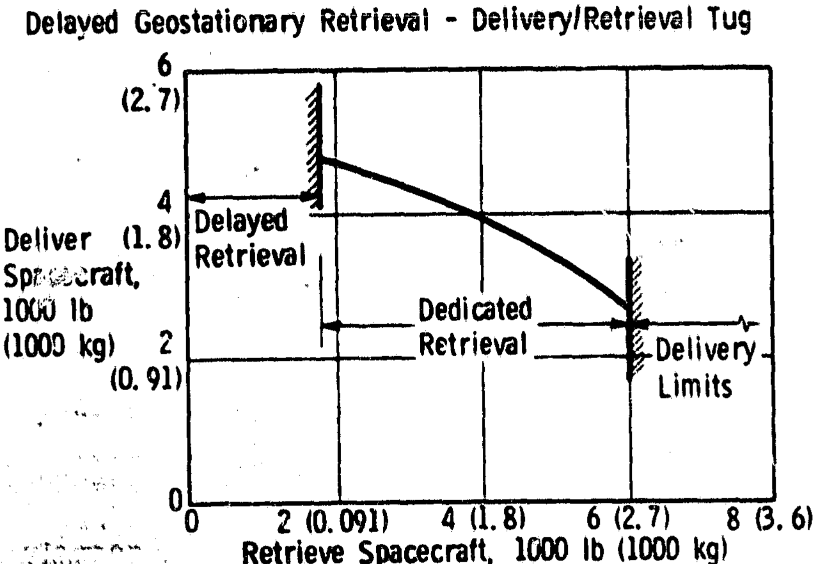


Fig. 2.1-3 Trapeze Staging Technique

2.1.1.3.4 Delayed Retrieval - The basic geostationary delivery capability of the one-stage Tug is considerably higher than the identified requirement, while its retrieval capability is considerably less. As an example, Fig. 2.1-4 shows the capability of the delivery-only and delivery/retrieval Tugs recommended for Final Option 2. Note that the heaviest geostationary spacecraft identified in the mission model is 5500 lb (2495 kg). Delayed retrieval is a technique to split a delivery mission and a retrieval mission in some other ratio than the 4900 up/1800 down tabulated for the delivery/retrieval Tug. The technique is to deliver a spacecraft smaller than 4900 lb (2223 kg) on an initial Shuttle mission, and use the remaining energy to partially deorbit the spacecraft to be retrieved. On a subsequent Shuttle mission, the delayed retrieval is completed. Thus, two missions are completed with two Shuttle flights. The relationship between the delivered and retrieved spacecraft weight achievable is shown in Fig. 2.1-4. This technique allows retrieval of spacecraft that are much heavier than any specified in the NASA/DOD mission model for this study.



Configuration	Geostationary Spacecraft, lb (kg)		
	Delivery	Retrieval	Round Trip
Delivery-Only	6,000 (2,722)	N/A	N/A
Delivery/Retrieval	4,900 (2,223)	1,800 (816.5)	1,350 (612.3)

Fig. 2.1-4 Capabilities of Final Option 2 Tugs

2.1.1.3.5 Planetary Missions - The lower-energy planetary missions can be achieved by a Tug operating in the reusable mode. Since the Tug achieves hyperbolic escape velocities, mission design is highly time critical if velocity losses are to be kept within reasonable bounds. The "perigee propulsion" approach to this mission is illustrated in Fig. 2.1-5. Principal optimization parameters are the split between first and second inject burns (points 1 and 2 in Fig. 2.1-5), minimization of the time the Tug stays in its hyperbolic escape orbit before a retro burn (3), and a trade between a longer return orbit period and the degrading effect of Shuttle Orbiter nodal regression as mission time increases. This optimization has been studied in detail by NASA Lewis in support of these contractual studies. The capture analysis in this study has used a net one-way vehicle loss of 900 fps (274.3 m/sec) for low-energy planetary missions.

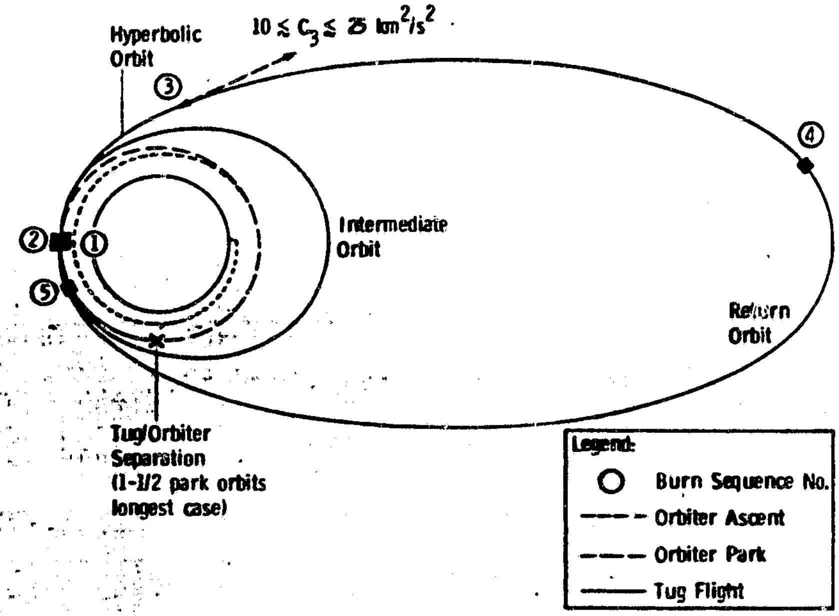


Fig. 2.1-5 Planetary Mission with Perigee Propulsion

The higher-energy planetary missions require kick stages and/or expendable Tug modes. Associated mission designs are somewhat simpler, and generally have lower velocity losses. See Vol 6.0 of the *Selected Option Data Dump* (Ref 5.8).

2.1.1.3.6 Mission Capture Performance - Mission capture data evolved during the study were based on general performance curves and mission velocity budgets developed with certain basic assumptions. These assumptions and resulting data are in Vol 4.0 of the *Selected Option Data Dump* (Ref 5.8). A brief overview is presented here.

General performance curves reflect a simplified analytical model of Tug flight. Tug performance is represented by the ideal rocket equation, and the mission velocity budget for Tug return modes assumes that inbound and outbound velocity requirements are equal. Mission velocity requirements are increased by 1.7% to account for Tug performance dispersions. Arbitrary weight/engine performance descriptions are used to account for ACPS propellant use (assumed to be an expendable inert, increasing propellant flow but not increasing thrust). No thrust or trajectory shaping losses are included in the curves.*

Specific mission performance requirements compared to these general performance curves reflect an effective mission velocity. This was derived by establishing the spacecraft capability of a particular configuration worked in detail against the mission velocity budget. The velocity budget reflects thrust losses, nodal corrections, midcourse and rendezvous propellant requirements, etc, of a realistic mission plan. Effective mission velocity is defined as the velocity at which the general performance curves indicate the same spacecraft capability as that derived from the detailed evaluation. Once established for a specific configuration, this effective mission velocity was used for all configurations. A summary of effective mission velocities is shown in Vol 4.0, Table 1.1-1 of the *Selected Option Data Dump* (Ref 5.8).

2.1.2 Mission Capture Analysis

2.1.2.1 Mission-Model/Program-Option Ground Rules - The basic purpose of the capture analyses was to evaluate various Tug design approaches against standardized mission models to obtain a common evaluation of their merit. As shown in Fig. 1-1, capture analysis was initiated early and continued throughout the entire study, contributing to both subsystem and system selections.

The mission capture analysis was used to establish the number and schedule of flights required to perform all missions in a particular model. These data were then fed into the programmatics analysis to establish Tug fleet size, support requirements, and total associated program cost. This array of data provides information required to make fair comparisons among, and eventually a selection from, various configuration/program options.

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*The only exception to this rule is for the Interim Tug recommended for Final Option 1, where a degraded engine thrust is accounted for by an equivalent specific impulse degradation.

DDT&E costs for the final selected options as presented in the *Selected Option Data Dump* (Ref 5.8) are presented in Table 1.4-3. The cost of the first Tug, which carries an operational payload, is included. Kick-stage (Space Tug auxiliary stage) costs are also included.

Additional Analysis (para 3.6) shows that the DDT&E costs can be reduced considerably by revising certain ground rules and assumptions.

1.4.4 Minimum Production and Operations Costs through Reusability

The reusability of the final option definitions provides for minimum production and operations costs. For example, Final Option 3 requires only 16 Tugs and 9 kick stages to accomplish 352 flights. This includes four reliability losses (one loss per hundred flights) and eight Tugs, which are expended on high-energy planetary missions.

Table 1.4-4 presents fleet size and operational data for each final option. The number of flights differs from that shown in Table 1.4-1 because the number of flights has been limited in the first two years of operations and reliability losses have been added. (See *Guidelines*, (para 1.2.) The stage-and-a-half configuration (Final Option 3A) suffers from lack of reusability due to the large number of drop tanks expended.

Tables 1.4-5 and 1.4-6 present production and operating costs, respectively, for the final option definitions presented in the *Selected Option Data Dump* (Ref 5.8). Additional analysis (para 3.6) shows that production and operating costs can be reduced considerably by revising certain ground rules and assumptions used.

1.4.5 Programmatics and Transportation Costs

Table 1.4-7 summarizes total transportation costs for each final option definition as presented in the *Selected Option Data Dump* (Ref 5.8). The phased-development program (Final Option 3) returns the most benefits (in terms of the number of missions achieved) for the cost expenditure. The stage-and-a-half (Final Option 3A) requires fewer flights for mission model capture, but the Shuttle cost savings are more than offset by the higher Tug costs.

IOC sensitivity studies indicate that stretching out the development time can reduce annual peak funding requirements, although this increases total DDT&E costs slightly. Peak funding should be a key factor in choosing the optimum program for the Tug.

Sensitivity studies also show that use of the DOD programmatic approach reduces risk, but delays production, producing an uneven distribution in annual funding requirements. It is therefore recommended that commit-to-production not be contingent on flight test evaluation.

Table 1.4-3 Development Cost Breakdown

WBS	Identification	Final Option, $M 1	2	3	3A
01	Project Management	15.2	15.9	17.3	19.5
02	Systems Engineering	22.0	27.7	29.1	31.1
03	Tug Vehicle Main Stage	85.9	140.8	181.1	192.0
04	Tug Vehicle Auxiliary Stage	26.1	18.1	26.1	26.1
05	Logistics	2.4	2.6	2.9	3.1
06	Facilities	19.6	19.6	19.6	19.6
07	GSE	23.4	26.2	27.6	29.0
08	Vehicle Test	40.8	45.4	47.3	57.4
11	Flight Operations - DOD	0.3	0.3	1.0	1.0
12	Flight Operations - NASA	1.1	1.1	1.7	1.7
	Total	236.8	297.7	353.7	380.5

Table 1.4-4 Production and Operations Data

	Final Option 1	2	3	3A
Launch Operations (Years)	11	7	11	11
Crew Size - ETR	96	142	142	156
- WTR	48	86	86	100
- Central Support	10	14	12	14
- Total	154	242	240	270
Number of Flights* - NASA	119	139	196	189
- DOD	108	115	156	155
- Total	227	254	352	344
Expendables - Tugs (Main Stage)	10	6	8	8
- Kick Stage 10	3	5	5	5
- Kick Stage 1.5	4	-	-	-
- Kick Stage 10/1.5	4	-	4	4
- Drop Tanks	-	-	-	292
Fleet Size - Tugs (Main Stage)	15	13	16	16
*Includes reliability losses & limited flights in first two years	3	3	4	4

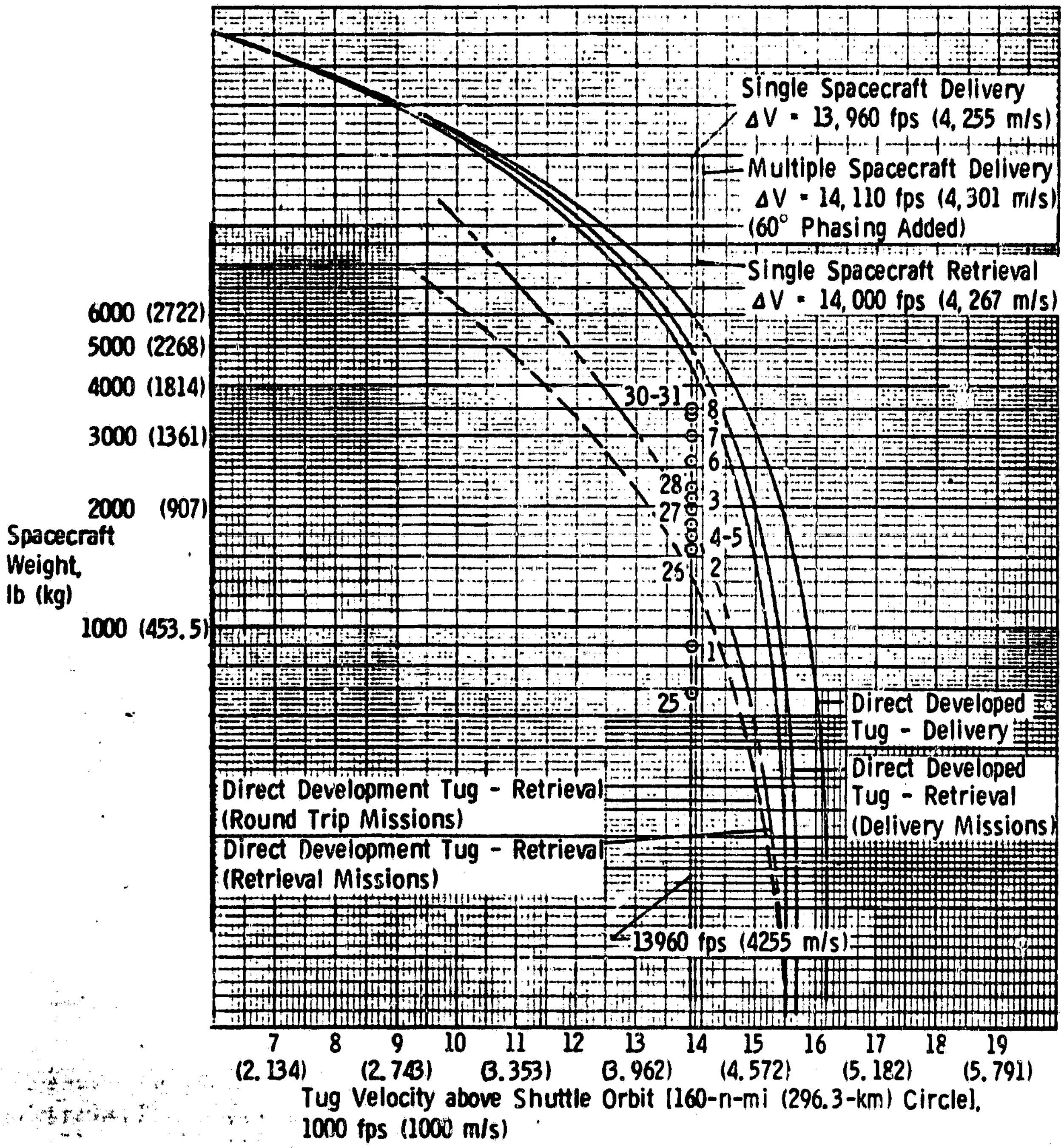

Fig. 2.1-6 Final Option 2 NASA and DOD Geostationary Missions with Single Stage

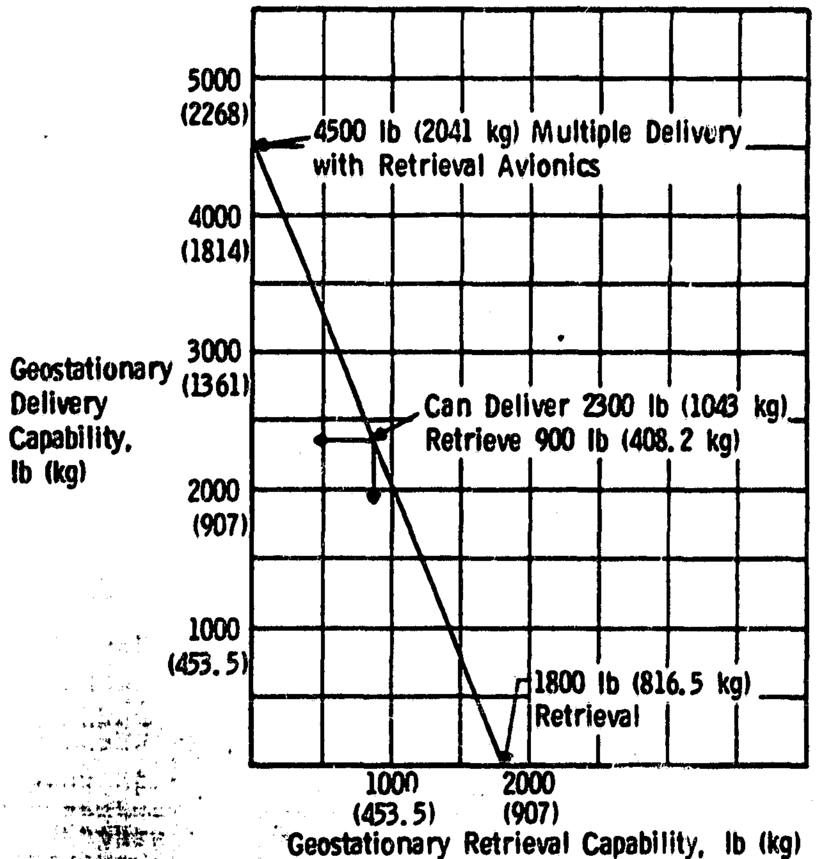

Fig. 2.1-7 Unequal Round-Trip Capability for Final Option 2 Direct-Developed Tug-Retrieval

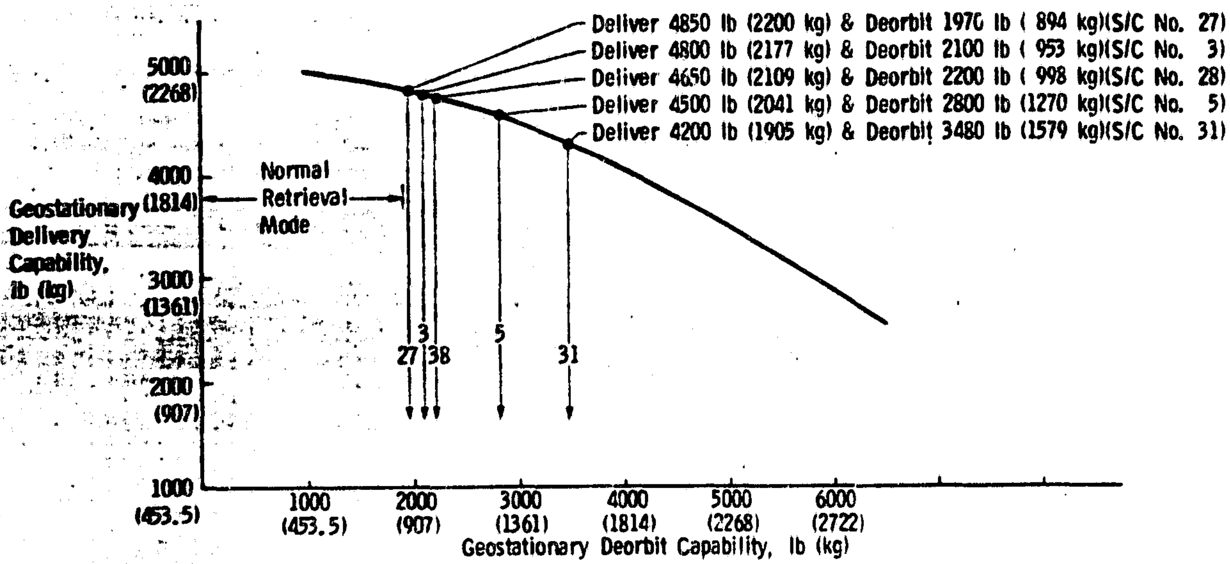

Fig. 2.1-8 Direct-Developed Tug-Retrieval Deorbit Capability for DRFM

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A generally similar approach was followed in each of the remaining mission categories--midinclination, polar, and planetary. For midinclination and polar missions, performance data show reduced Shuttle capability. For the planetary missions, kick stages are used, as are expendable modes. A general summary of Final Option 2 data is shown in Fig. 2.1-9. An example of the net result of these analyses is shown in Table 2.1-4. This illustrates that 437 spacecraft deliveries/retrievals are accomplished with 293 flights. A complete array of mission capture, flight schedules, and additional capture potential for this study is presented in Vol 4.0 of the *Selected Option Data Dump* (Ref 5.8).

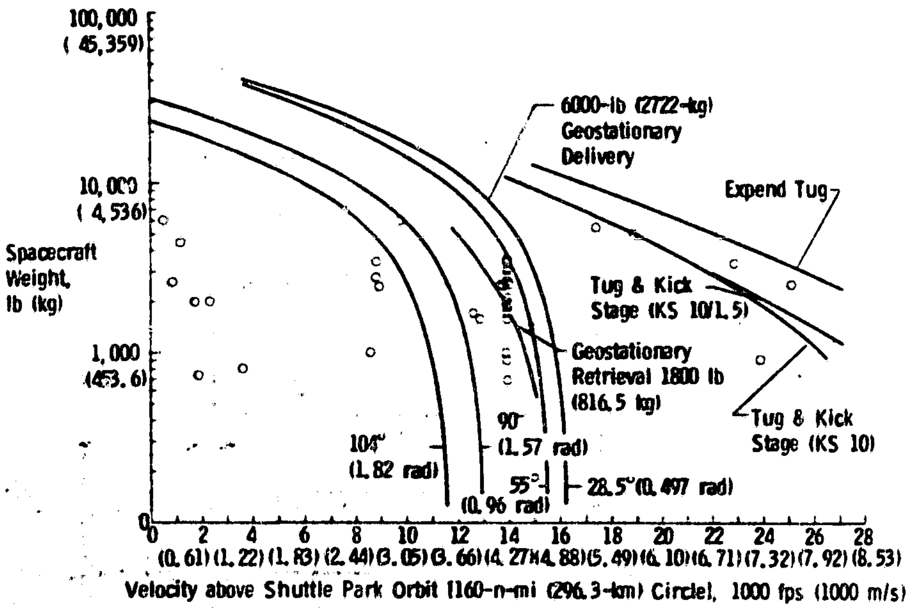

Fig. 2.1-9 Final Option 2 Mission Model and Tug Performance

2.1.2.3 Mission Capture Summary Results

a. Final Option 1 - This option was devised to evaluate the possibility of saving development and total program costs by lowering mission goals--and the expense of the Tug required. An Interim Tug configuration was defined with a low-development-cost engine, battery power, and no retrieval capability. Principal effects of these selections were reduced spacecraft performance capability, 3800-lb (1724-kg) geostationary delivery, and reduced flight endurance (36 hr). The vehicle can perform all missions identified for this option. Note that the 36-hr endurance is the reason DOD missions 36, 37, and 38 were excluded from the model. The flight schedule associated with the option is shown in Fig. 2.1-10.

Table 2.1-4 Final Option 2 Flight Summary (100% Capture)

Flight Modes & Tug Configurations	Calendar Year											Total
	80	81	82	83	84	85	86	87	88	89	90	
Shuttle Flights					45	43	41	41	36	42	45	293
Tug Flights					45	43	41	41	36	42	45	293
Delivery Flights, Direct Development-Delivery												
Tug (Single Spacecraft Flights)					5	2	5	4	5	4	4	29
Tug (Multiple Spacecraft Flights)					3	2	1	5	4	7	2	24
Tug + Kick Stage 10							3	2				5
Tug + Kick Stage 10/1.5					2							2
Tug (Expended)					2		1	1		3	1	8
Retrieval Flights												
Direct-Developed Tug-Retrieval					9	3	10	3	8	1	6	40
Delayed Retrieval Flights												
Direct-Developed Tug-Retrieval					6	11	3	6	2	8	10	46
Delivery & Deorbit for Delayed Retrieval												
Direct-Developed Tug-Retrieval					6	11	3	6	2	7	8	43
Dedicated Deorbit for Delayed Retrieval												
Direct-Developed Tug-Retrieval										1	2	3
Roundtrip Flights												
Direct-Developed Tug-Retrieval					10	9	14	10	14	10	10	77
Unequal Roundtrip Flights												
Direct-Developed Tug-Retrieval					2	5	1	4	1	1	2	16

		80	81	82	83	84	85	86	87	88	89	90	Total
Mission Model	Spacecraft Delivered					37	37	32	41	34	43	34	258
	Spacecraft Retrieved					27	28	28	23	25	20	28	179
	Total					64	65	60	64	59	63	62	437

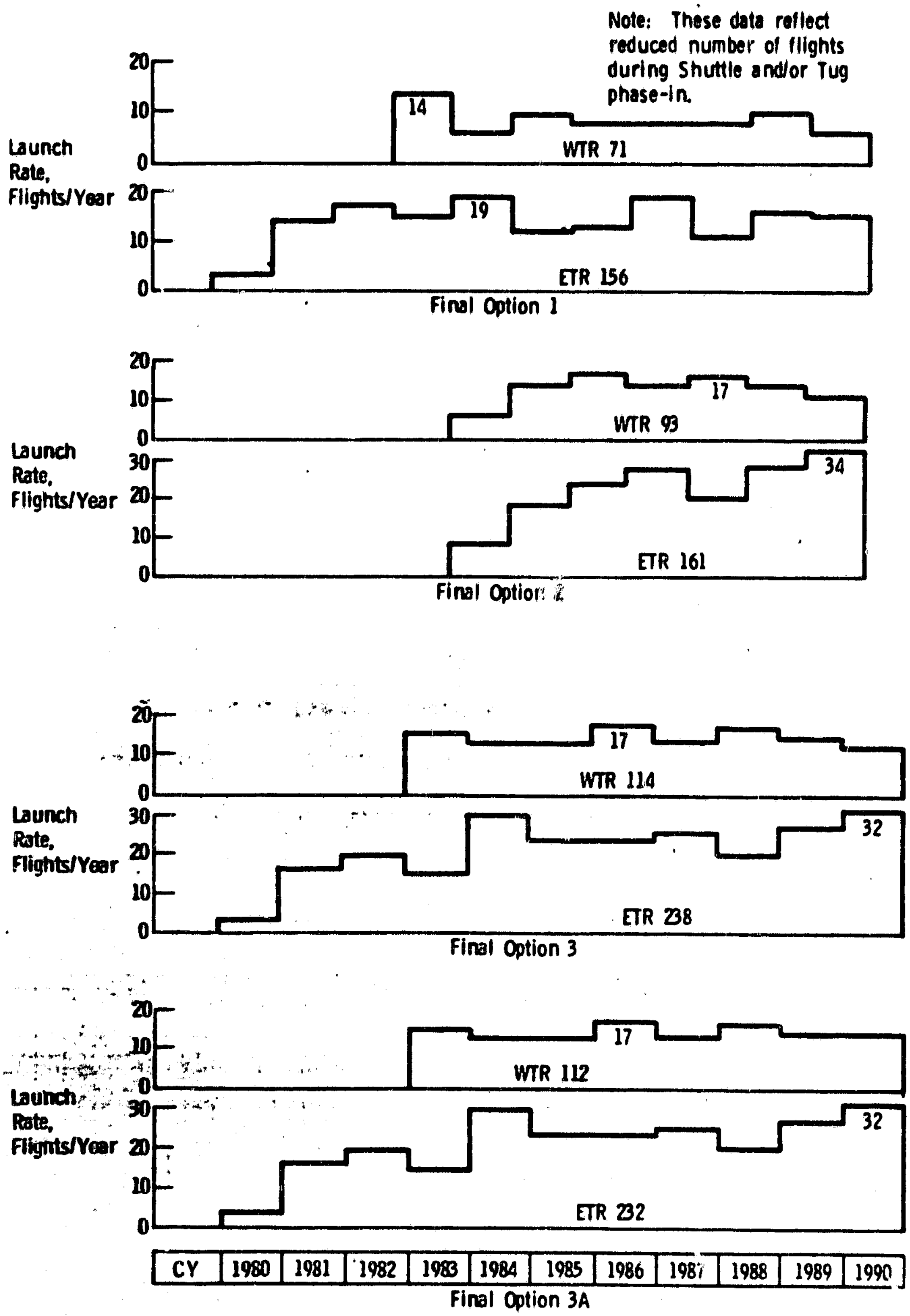

Fig. 2.1-10 Annual Flight Summaries

Additional missions, not included in the Final Option 1 mission model due to performance or flight endurance constraints, were evaluated to determine additional capture potential. To capture the heavier low-cost-design planetary spacecraft, dual Shuttle flights with Tugs ganged on orbit are required. DOD missions 36, 37, and 38 can be accommodated by adding batteries to achieve the required mission duration, while retaining adequate spacecraft performance. DOD mission 29, a geostationary sortie mission, is beyond the ability of this configuration.

A more detailed breakdown and explanation of mission capture data for this and other options are included in Vol 4.0 of the *Selected Option Data Dump* (Ref 5.8).

b. Final Option 2 - This option involved the case in which ultimate Tug capability is developed directly for a delayed IOC date. The ultimate single-stage Tug defined was the Direct-Developed Tug-Retrieval. This vehicle incorporates a new high-performance engine, solar panels, and subsystems required for retrieval. The Direct-Developed-Tug-Delivery configuration deletes the retrieval capability; otherwise, the two configurations are identical. These Tugs (plus kick stages) can perform all missions identified in the Final Option 2 mission model. The resulting flight schedule is shown in Fig. 2.1-10.

The additional capture potential evaluated in this case included geostationary spacecraft heavier than the 3500-lb (1588-kg) model goal, low-cost-design planetary spacecraft, and the DOD geostationary sortie mission. The heavy geostationary spacecraft can be accommodated by the delayed retrieval mode. Most of the low-cost planetary spacecraft can be accommodated in the reusable mode or by expending a Tug. Mission 22 requires ganging on orbit and a Tug expenditure. The DOD geostationary sortie mission cannot be accommodated.

c. Final Option 3 - This option dealt with a phase-developed single-stage Tug. During the early Shuttle years, a vehicle with a (Phased Tug-Initial) relatively low-cost engine and no retrieval capability was used. This vehicle was then evolved to retrieval capability with a new engine (Phased Tug-Final-Delivery and Phased Tug-Final-Retrieval). These Tugs (plus kick stages) can perform all missions identified in the Final Option 3 mission model. The resulting flight schedule is shown in Fig. 2.1-10.

The additional capture potential for this option is essentially identical to that described for Final Option 2 because it deals with the same vehicles and the same candidate spacecraft.

d. Final Option 3A - This option is a phase-developed stage-and-a-half Tug parallel to the Final Option 3 configuration. The flight schedules are shown in Fig. 2.1-10. Note that Final Option 3A requires eight fewer flights than Final Option 3. This shows the advantage of higher performance and shorter length of the stage-and-a-half configurations.

An analysis of additional capture potential was not required for Final Option 3A.

2.2 Subsystem Requirements and Evaluation

This section describes the Tug subsystem analytical and conceptual hardware design effort performed during this study. The effort (Task 2) started concurrently with the Mission Requirements Analysis (Task 1) at the beginning of the study and continued throughout Configuration Analysis (Task 3) and Program Definition (Task 5), as the specific Tug configurations were reiterated and further defined. The effects of Programmatics and Cost Analysis (Task 4) was integrated into the subsystem analysis where required.

Because the use of existing subsystems and components was to be emphasized in this study, collecting and analyzing technical and cost data on all potential subsystems and/or components was the initial effort. A parallel effort was analysis of Tug subsystem/component functional requirements.

Comparison of the data collected against the functional requirements was justification for rejection of many subsystems/components for one or more of the following reasons: obsolescence according to 1979 standards, excessive weight and volume, excessive electrical power required, no longer in production--tooling not available, failure to meet safety or reliability requirements, high cost, etc.

Various trades and parametric analyses were conducted within each subsystem to eliminate unsatisfactory candidates. The one or more candidate subsystems judged satisfactory for consideration in the overall Task 3 Tug configuration synthesis process were identified as selected subsystem candidates.

A summary discussion of the total subsystem activities by subsystem is presented in the following paragraphs, including, in each case, a description of the subsystem(s) used in Final Options 1, 2, 3, and 3A. Also included are discussions of the Tug payload docking and separation modules and kick-stage configurations.

2.2.1 Structures Subsystem

2.2.1.1 Requirements - The structural requirements are basically derived from other subsystem requirements; thus, the structure must provide for:

1) Propellant load packaging;

2) Integration and mounting of avionics components;

3) Docking mechanism (for some options);

4) Integration and mounting of pressurization system;

5) Integration and mounting of thermal control system;

6) Suitable location and orientation of ACPS motors;

7) Meteoroid protection;

8) Interface provisions for mating with both the Orbiter and a Tug payload.

In addition, the structure must sustain all design load conditions without excessive or detrimental deflections and not fail under ultimate loads. It must meet the above criteria in an efficient manner, minimizing structural weight.

2.2.1.2 Candidates Considered - There were four basic vehicle concepts derived from various approaches considered to capture the mission model. These consisted of:

1) A single-stage vehicle (designators IA through IH) sized to carry 57,000 lb (25,855 kg) of propellant and limited to no more than 35 ft (10.7 m) in length;

2) A single-stage vehicle (designators IIA through IIC) sized to carry 57,000 lb (25,855 kg) of propellant, but limited in length to 17.5 ft (5.3 m) so that, by off-loading propellant, two-stage operation could be achieved;

3) A two-stage combination of vehicles (designators IIIA through IIIH) each sized for 28,500 lb (12,927 kg) of propellant and with their total length limited to no more than 35 ft (10.7 m);

4) A stage-and-a-half vehicle (designators IVA through IVE) with the drop tanks sized to carry either 50% or 80% of the total 57,000 lb (25,855 kg) of propellant. The tanks were designed for an oxidizer/fuel mixture ratio of 2:1 by weight.

For these vehicle concepts, various candidates were evaluated for the main propellant tanks, nontank or skirt structure, and engine thrust structure. For the tankage evaluation, dome shapes, structural arrangement, and materials were all considered. Dome shapes evaluated were hemispherical and $\sqrt{2}$ elliptical, while the arrangements consisted of isolated tandem tanks, isolated side by side, common dome, tandem, and common wall. Materials considered were 2219-T87 aluminum and Ti-6Aℓ-4V titanium alloy. For these trades, the tanks were sized using the proposed operating and relief pressures along with the factors-of-safety approach from MSFC-HDBK-505 (Ref 5.18). This approach resulted in the following pressures.

Pressure	Fuel Tank psi	Fuel Tank N/cm^2	Oxidizer Tank psi	Oxidizer Tank N/cm^2
Operating	16	11	30	20.7
Relief	30	20.7	60	41.4
Yield (1.1 x relief)	33	22.8	66	45.6
Ultimate (1.4 x relief)	42	29	84	58

For the nontank, or skirt structure, both closed shell and open truss were considered. These consisted of aluminum honeycomb (graphite epoxy face sheets over aluminum core), aluminum skin-stringer, aluminum integral-rib-stiffened, and graphite-epoxy composite tubular-truss construction. The studies were conducted using an ultimate running axial load of 637 lb/in. (1116 N/cm).

The candidates chosen for engine thrust structure consisted of both open truss and closed cone. The open-truss structures evaluated were made of titanium, aluminum, and graphite epoxy. The closed-cone configurations consisted of titanium skin-stringer construction and a composite graphite-epoxy honeycomb. The engine thrust structure was sized using 15,000 lb (66,723 N) of thrust and a dynamic factor of 2.0 applied to the thrust load.

2.2.1.3 Selection Methods - The first step in the screening process was to list requirements that a candidate must meet, such as schedule, physical compatibility with spacecraft and Orbiter, reusability, refurbishment capability, and the minimum required performance. These screening criteria were applied to each Tug candidate structural arrangement, and those meeting all the "must" requirements were then subjected to a more detailed comparative screening. This screening process compared on a relative basis such things as fabrication costs, reliability, complexity, safety, producibility, and ease of handling.

2.2.1.4 Selected Subsystem Candidates - During this Task 2 effort, 25 different structural arrangements were put through the coarse screening with four single-stage, two two-stage and one stage-and-a-half configuration being rated high enough for consideration in the Task 3 vehicle synthesis analyses. A summary of these selected candidates is shown in Table 2.2-1, along with rejected concepts.

2.2.1.5 Final Option Definition - As a result of the configuration synthesis, a single-stage vehicle (IA2 type) was the preferred configuration for each of the seven capability options. This single-stage structural concept was carried over to Task 5, with NASA concurrence, for Final Options 1, 2, and 3.

Table 2.2-1 Basic Structural Concepts Summary

Designator	Description
IA thru IH	Single stage, 57,000 lb (25,855 kg) propellant, mixture ratio 2:1
Selected Candidates	
IA1	Isolated tanks, Titan III Stage II tank arrangement
IA2	Isolated tanks, fuel tank forward, elliptical domes
IA3	Isolated tanks, equal-volume tanks (MR 1.65:1)
ID	Common-dome tanks, hemispherical domes
Rejected Concepts	Isolated tanks, spherical domes Common-wall cylinder inside sphere Common-wall cone inside sphere Four isolated tanks Spherical cap inside a spherical tank Common elliptical domes
IIA thru IIC	Single-stage, max length 17.5 ft (5.3 m), 57,000 lb (25,855 kg) propellant
Selected Candidates (none)	
Rejected Concepts	Separate tanks, spherical segment domes, common dome, oxidizer elliptical, fuel conical
IIIA thru IIIH	Two-stage, 28,500 lb (12,927 kg) propellant per stage
Selected Candidates	
IIIC	Common-dome tanks, elliptical domes
Rejected Concepts	Isolated tanks, elliptical domes Isolated tanks, spherical domes Common-dome tanks, spherical domes Spherical cap inside a sphere Common-wall cone inside sphere Common-wall cylinder inside sphere Four isolated tanks
IVA thru IVE	Stage-and-a-half, various propellant splits & tank arrangements
Selected Candidates	
IVE	20/80 propellant split, core plus 2 drop tanks, common elliptical domes
Rejected Concepts	20/80 propellant split, $\sqrt{2}$ common domes on core, spherical domes on 4 drop tanks 50/50 propellant split, $\sqrt{2}$ common domes on core, spherical domes on 4 drop tanks 50/50 propellant split, 4 isolated tanks on core, 4 separate drop tanks, spherical dome 50/50 propellant split, $\sqrt{2}$ common domes on core, 1 drop tank with $\sqrt{2}$ common dome

a. Final Options 1, 2, and 3 - Single-stage structural arrangement and details are basically the same for all three final options. Final Option 1 is sized for 57,000 lb (25,855 kg) total propellant for delivery-only missions, and, to optimize retrieval capability, Final Options 2 and 3 are sized for 60,000 lb (27,216 kg) total propellant. Figure 2.2-1 and Table 2.2-2 show this arrangement. All vehicles have isolated tandem titanium tanks, with $\sqrt{2}$ elliptical domes and are 10 ft (3.05 m) in diameter. Forward skirts are of aluminum skin-stringer construction, providing for easy equipment mounting and the preferred material for the thermal problem associated with mounting electronics components in that location. The between-tanks and aft skirts for all three final options are composite honeycomb with graphite-epoxy face sheets and aluminum cores.

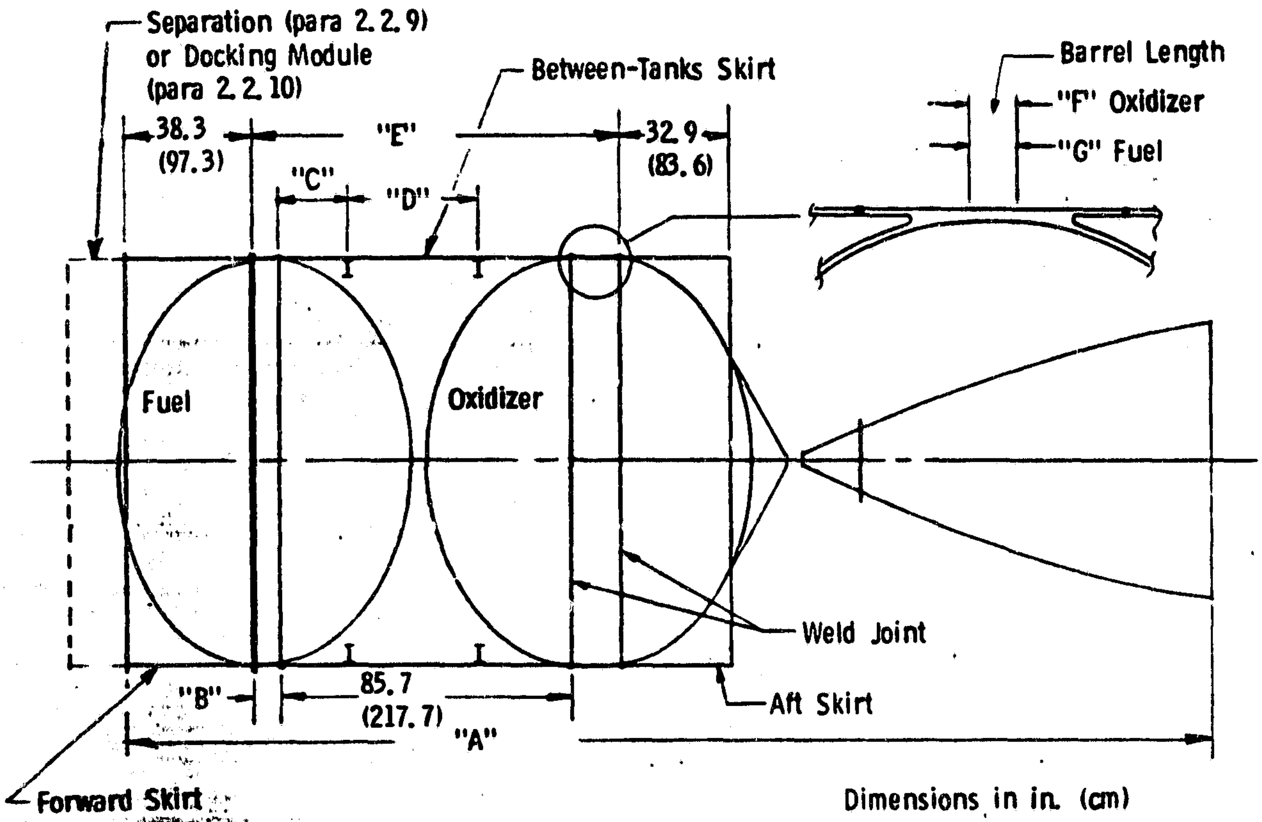

Fig. 2.2-1 Single-Stage Configuration for Final Options 1, 2, and 3

Table 2.2-8 Final Option Configuration Dimensions

Final Option	Configuration	Total Propellant Load for 1.9 MR		Dimension, in. (cm)													
				A		B		C		D		E		F		G	
		lb	kg	in.	cm	in.	cm	in.	cm	in.	cm	in.	cm	in.	cm	in.	cm
1	Delivery Only, 1979	57,000	25,855	326	828	7.4	18.8	19.4	49.3	38.5	97.8	109	277	9.65	24.5	1.5	3.8
2	Delivery Only, 1983	60,000	27,216	323	820	10.4	26.4	17.4	44.2	40.5	102.9	115.5	293.4	13.15	33.4	4.5	11.4
2	Retrieval, 1983	60,000	27,216	323	820	10.4	26.4	17.4	44.2	40.5	102.9	115.5	293.4	13.15	33.4	4.5	11.4
3	Delivery Only, 1979	60,000	27,216	333	846	10.4	26.4	22.4	56.9	35.5	90.2	115.5	293.4	13.15	33.4	4.5	11.4
3	Delivery/ Retrieval, 1983	60,000	27,216	323	820	10.4	26.4	22.4	56.9	35.5	90.2	115.5	293.4	13.15	33.4	4.5	11.4
3A	Delivery Only, 1979	60,000 20% Core 80% Drop Tanks	27,216	275	699	--	--	--	--	--	--	--	--	--	--	--	--
3A	Delivery/ Retrieval, 1983	60,000 20% Core 80% Drop Tanks	27,216	265	673	--	--	--	--	--	--	--	--	--	--	--	--

b. *Final Option 3A* - In addition, at NASA direction, a stage-and-a-half vehicle (Fig. 2.2-2 and Table 2.2-2) was selected for further study to satisfy Final Option 3A. The core vehicle is 6 ft (1.83 m) in diameter with isolated tandem titanium tanks with $\sqrt{2}$ elliptical domes. The forward, between-tanks, and aft skirts are all of aluminum skin-stringer-frame construction, while the thrust structure is a truss. The drop tanks, two fuel and two oxidizer, 4 ft (1.22 m) in diameter with hemispherical domes, are made of aluminum. Trusses and fittings that tie the drop tanks to the core and the Tug to the Cradle are made of aluminum and designed so the trusses remain with the core at separation, thus simplifying the Tug/cradle interface.

Additional detailed structural data may be found in Vol 5.0, Sec I of the *Selected Option Data Dump* (Ref 5.8).

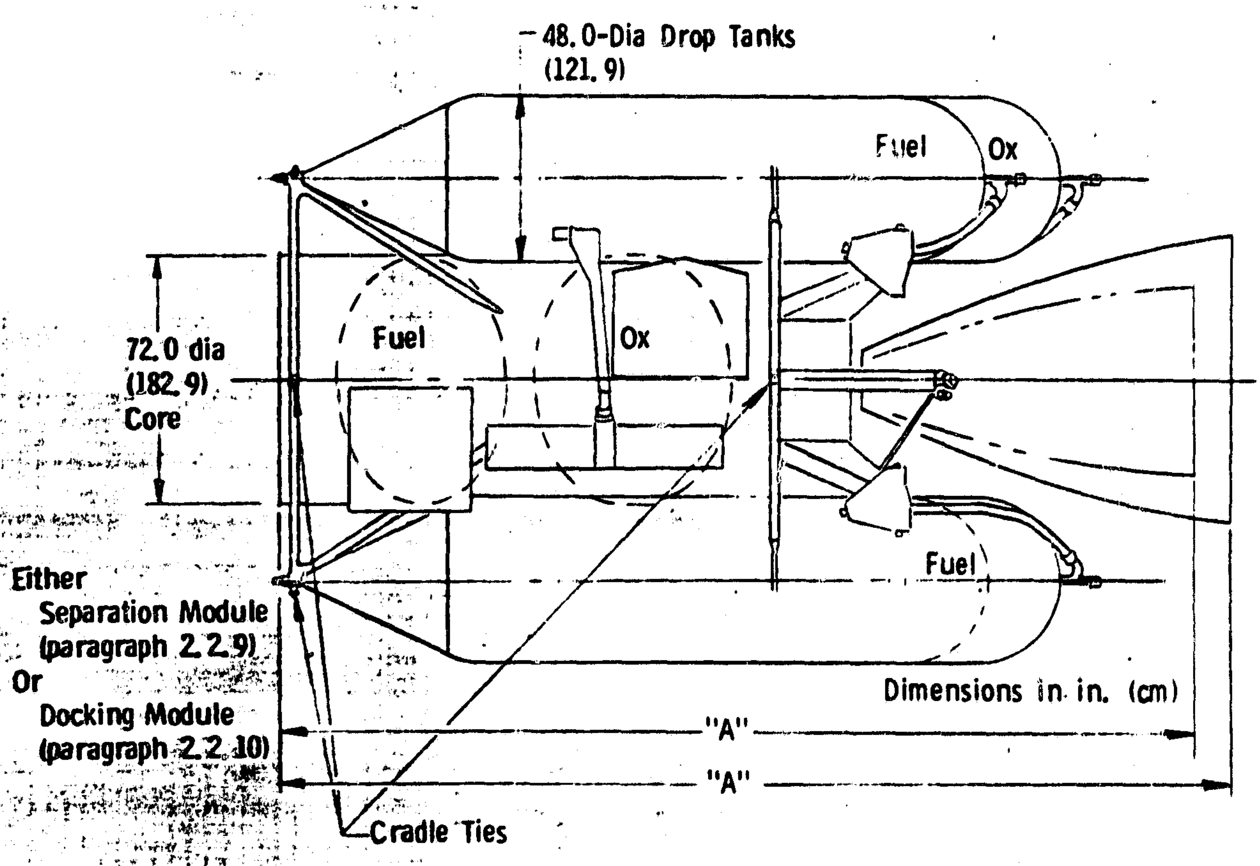

Fig. 2.2-2 Stage-and-a-Half Configuration for Final Option 3A

2.2.2 Thermal-Control Subsystem

2.2.2.1 Requirements - The thermal-control subsystem requirement is to maintain the Tug subsystems within allowable temperature limits for ground, launch, orbit, postorbit, and landing conditions. The orbital time requirement varied from 36 hr to 7 days--up to 30 days as a goal. Although it is desirable that the Tug thermal-control subsystem not require a selective Tug orientation, certain spacecraft may require it to perform thermal maneuvers. Because the Tug avionics subsystem must be capable of accepting changes in mission assignment or spacecraft ephemeris before launch, and because certain Tug subsystems/components will be operating before launch and continuously thereafter, the thermal control subsystem design must provide the necessary operational flexibility for these conditions.

2.2.2.2 Candidates Considered - Design and development of the Tug thermal-control subsystem is a highly iterative process that depends on the Tug configuration, subsystems selected, types of missions to be flown, and requirements for or limitations on thermal maneuvers.

Thermal-control methods considered for the many Tug configurations included:

1) Passive control through the use of multilayer insulation (MLI);

2) Passive control through the use of optical solar reflectors (OSR);

3) Passive control through the use of paint patterns and special surface finishes;

4) Active control through the use of fluid loops, heat pipes, and radiators;

5) Various combinations of these.

Active control would use the waste heat from the fuel cell when it was used as a power source.

2.2.2.3 Selection Methods - Thermal-control subsystems were not selected as separate subsystems independent of other Tug subsystems; rather, selection of the Tug configuration and other subsystems dictated the thermal-control system selection.

2.2.2.4 Selected Subsystem Candidates - Both active and passive thermal-control subsystems were retained for consideration in Task 3 because one selected pressurization subsystem candidate required the use of cryogenics.

2.2.2.5 Final Option Definition - On the basis of reduced cost, complexity, and weight, passive thermal control was selected for use on all final options.

a. Final Options 1, 2, and 3 - Definition of the thermal-control subsystems for the final-option single-stage vehicles required thermal analysis and modeling as briefly described in the following paragraphs.

A steady-state thermal model was prepared to evaluate the feasibility of passive thermal control of the avionics compartment. An 18-node model was used to simulate the peripheral temperature gradient in the walls, and one node represented the average effect of the avionics on wall temperatures. Results showed that a maximum wall temperature of 70°F (21°C) was necessary to keep the higher-powered components within allowable temperature limits.

A 67-node thermal model was prepared for one of the earlier single-stage configurations, using the Martin Marietta Interactive Thermal Analysis System (MITAS) program. Cases were run to evaluate the use of MLI on the propellant-tank side walls. It was determined that MLI on the side walls was unnecessary for most missions. In keeping with the propulsion subsystem design, external radiation properties were selected to provide a maximum steady-state propellant temperature of 70°F (21°C) for the maximum external heat-flux case. This was determined to be a 500-n-mi (926-km) circular orbit over the terminator, with the vehicle axis perpendicular to the Earth-Sun line.

An improved 270-node thermal model of single-stage Tug configurations is about 60% complete. The Martin Marietta Thermal Radiation Analysis System (TRASYS) program is used to compute radiation interchange properties and orbital fluxes, and the MITAS program is the thermal analyzer. The model is detailed down to the individual avionics component level. When completed, the model is expected to provide an early thermal analyzer capability for the Phase B study.

The passive thermal-control subsystem selected for use on the final option single-stage Tugs is described below.

Multilayer insulation (MLI) is used over the fore and aft ends of the Tug to create thermally compatible compartments for avionics equipment and consumables. The outside of the avionics compartment is covered with optical solar reflector (OSR) material to minimize absorption of solar energy. Sidewalls are painted to maintain a maximum propellant temperature of 70°F (21°C) with the Tug longitudinal axis perpendicular to the Earth-Sun line in a 500-n-mi (926-km) orbit. MLI and electrical heaters are used on temperature-sensitive components in the consumables compartment. High-power components, like the IMU and transmitter, require high heat-rejection provisions. This is accomplished by repackaging these components on a baseplate that then becomes part of the forward skirt skin, thus allowing for heat dissipation through radiation. Battery temperature control is provided through the use of heat pipes, connecting batteries to the forward dome of the fuel tank.

ACPS engines will cause plume heating of adjacent structures. The magnitude of the structural temperature rise is very sensitive to the engine duty cycle, and information to be available during the Phase B study will be needed to estimate this cycle. Items in the consumables compartment (aft skirt) are protected from engine plume heating by the base heat shield. Due to the high temperatures experienced in this region, Kapton is used for the MLI material.

b. Final Option 3A - The stage-and-a-half thermal-control subsystem presents a more difficult thermal design problem. No computer analysis was performed; however, a passive design is feasible, possibly at the expense of additional attitude constraints. Additional propellant feedline insulation and heaters are necessary due to the more complex plumbing arrangement. All external helium tanks and the hydrazine tank will require MLI and heaters. A Tug toasting maneuver may be required to provide thermal control for this configuration, and may require integration with any variable spacecraft orientation required.

Further analytical and hardware descriptive details may be found in Vol 5.0, Sec. I of the *Selected Option Data Dump* (Ref 5.8).

2.2.3 Guidance, Navigation, and Control Subsystem

2.2.3.1 Requirements - In general, GN&C subsystem requirements are to provide a high level of autonomous Tug flight capability to orbital conditions, consistent with delivery/retrieval mission requirements and the flight duration specified (from 36 hr to 7 days). This includes providing continuous information on the state vectors of position and velocity of the Tug, determining the direction of each of the principle axes of the Tug in inertial space, and forcing the state variables and attitude to those values required at the target points for a given mission.

Specific requirements for accuracy of spacecraft deployment, deployment, stability, attitude control during spacecraft rendezvous and docking, Tug/Orbiter separation and retrieval modes, and on-orbit relative to specific target orbital conditions are in the *Data Package* (Ref 5.7).

Level of autonomy was not specified. However, Autonomy Level II was selected as a baseline for the final options and is described in para 2.5.3.

2.2.3.2 Candidates Considered - In general, there were two generations of subsystems considered for all Tug configurations. The first employed components of existing design (generally heavy components) with 1979 availability; the second considered components of ultralightweight design that are in a brassboard development status, but deemed available by 1983.

Candidate components evaluated were star sensors, inertial measurement units (gimbaled and strap-down), horizon sensors, video cameras, rendezvous and docking radars, actuators, and ACPS rocket modules. Detailed tables of these candidates, along with technical data, are in the *First Review Presentation* (Ref 5.4) and Vol 5.0 of the *Selected Option Data Dump* (Ref 5.8).

2.2.3.3 Selection Methods - The approach used for GN&C subsystem selection is best described at the component level. Primary consideration was given to reliability, cost, and weight, but was not limited to these elements. Primary emphasis was placed on selecting the following units.

a. IMUs - Both the 1979 and 1983 systems were selected on the basis of safety and reliability. By employing these criteria, redundancy was a necessity, driving the IMU selection to skewed redundant strap-down units. The lightest unit available in 1979 and configured from existing modules, is the Hamilton Standard RSIMS at 64 lb (29.03 kg). For 1983 availability, the ultralightweight Autonetics MICRON IMUs, at 10 lb (4.54 kg) each, were selected. These are in flight test in the brassboard stage.

b. Star Tracker - Star tracker selection criteria were long mean time between failures and a reasonably low weight. This led to the selection of the Ball Brothers CT 401 unit, which is fully developed, low in cost, and has relatively good accuracy.

c. Horizon Sensor - The horizon sensor was chosen on the criterion of position update device, rather than the usual attitude update device. From a position update viewpoint, there is only one system that meets the requirements—the Quantic ETD 321B, Model IV. The horizon sensor is alternate equipment required only for Autonomy Level I DOD flights.

d. Rendezvous and Docking - Power, weight, and short-range resolution were the factors used in selecting the scanning laser radar (SLR) over more conventional RF ranging systems. The SLR is built by ITT and weighs about 60 lb (27.22 kg).

For the video system, the existing Apollo 15/16 TV camera system, at 13 lb (5.90 kg), was selected. Although a TV camera may not be required when docking to an attitude-stationary spacecraft, it will be required as an adjunct when docking to a rotating coning target spacecraft.

Rendezvous and docking is required only in Options 2, 3, and 3A.

2.2.3.4 Selected Subsystem Candidates - The GN&C candidates selected from Task 2 can be added to the total Avionics subsystem as kits to take advantage of the type of mission to be performed by the Tug with regard to weight, and operational complexity; i.e., on a delivery-only mission, the avionics installation would not include the rendezvous and docking radar or video units.

The following were selected as candidates for Tug configuration synthesis in Task 3:

Component	Remarks
Star Tracker	Ball Brothers CT401, fully developed, high reliability for all mission durations.
RSIMS	Hamilton Standard redundant strapdown inertial measurement system—not developed. All components are operational in Delta inertial guidance system (DIGS).
Horizon Sensor	Quantic ETD-321B, Model IV, meets Autonomy Level I.
Integrated Hydraulic Actuators	Tandem lightweight self-contained units. Avoids boil-off problems. No accumulators, lines, pumps, or reservoir required.

Component	Remarks
Valve Drive Amplifiers	Electronics required to drive integrated hydraulic actuators, auxiliary control propulsion system, and propellant valves.
ACPS Nozzles	Provides reaction pulses required for Tug attitude control during the coast phase of flight and roll control for the powered phase. Specific characteristics are in para 2.2.8.
Scanning Laser Radar	ITT--Available in 1983, lightweight, low power.
RF Rendezvous Radar	AN/APQ 148 or Apollo/LM--available in 1979.
Video Camera	RCA--available, Apollo 15/16 system. Proved in flight type test (FTT).

2.2.3.5 Final Option Definition

a. *Final Option 1* - The Final Option 1 GN&C subsystem is basically current state-of-the-art design; somewhat heavier, but less costly than the system selected in succeeding options.

Final Option 1 employs the AV-9(4) avionics subsystem shown schematically in Fig. 2.2-3. The GN&C portion of the subsystem consists of a skewed redundant strapped-down inertial measurement unit, star tracker, horizon sensor (for Autonomy Level I only), portions of the data management subsystem, integrated hydraulic actuators, and attitude-control valves and nozzles.

Navigation logic, guidance equations, powered-flight autopilot, and phase-plane autopilot algorithms are programmed in the flight computer part of the data management subsystem.

b. *Final Option 2* - This GN&C subsystem is lightweight and depends on continued development of some hardware now in the prototype or brassboard phase; specifically, the MICRON strap-down IMU made by Autonetics and the scanning laser radar made by ITT.

The Final Option 2 delivery-only avionics subsystem (AV-3) is shown in Fig. 2.2-4. The delivery and retrieval subsystem (AV-2) is shown in Fig. 2.2-5. The two subsystems are basically the same. When a retrieval mission is desired, the scanning laser radar, video camera and associated pan and tilt, and docking controls are mated to the bus through standard interface connectors. No rewiring of the Tug is necessary; equipment is merely plugged in and removed as required for various missions. Appropriate addressing and logic are incorporated into the data management subsystem.

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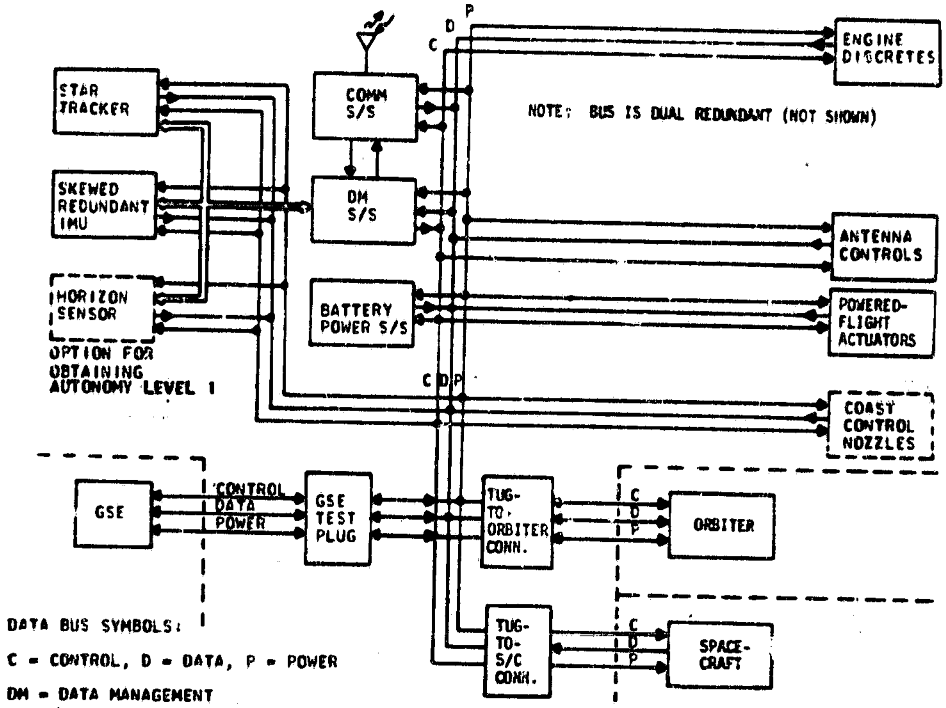


Fig. 2.2-3 Delivery-Only Tug Avionics Subsystem, AV-9(4), Autonomy Level II

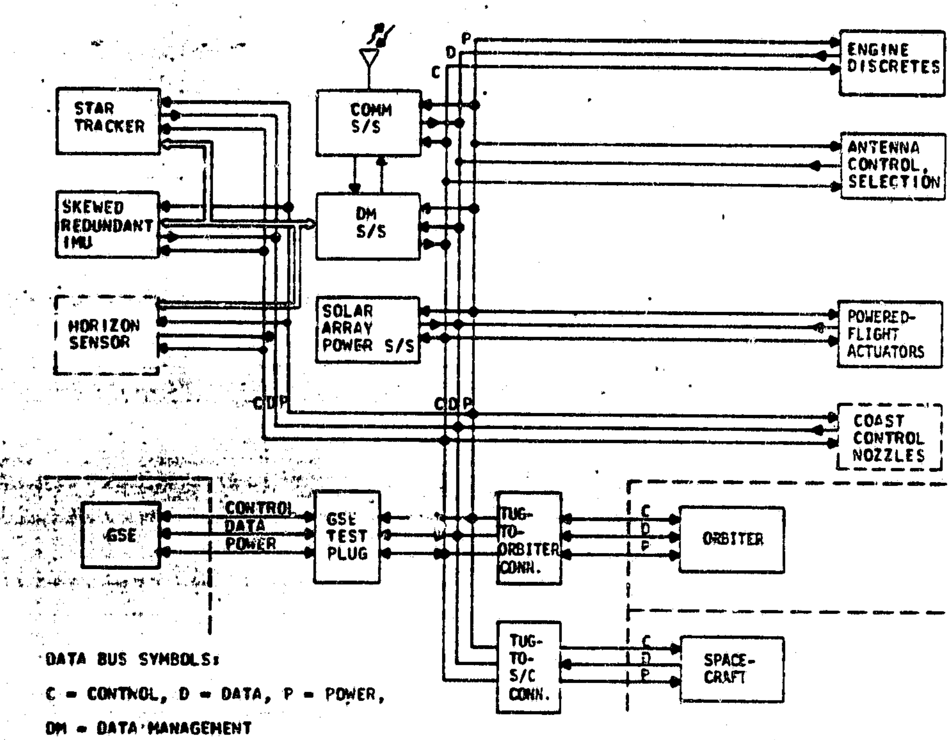


Fig. 2.2-4 Delivery-Only Tug Avionics Subsystem, AV-3, Autonomy Level II

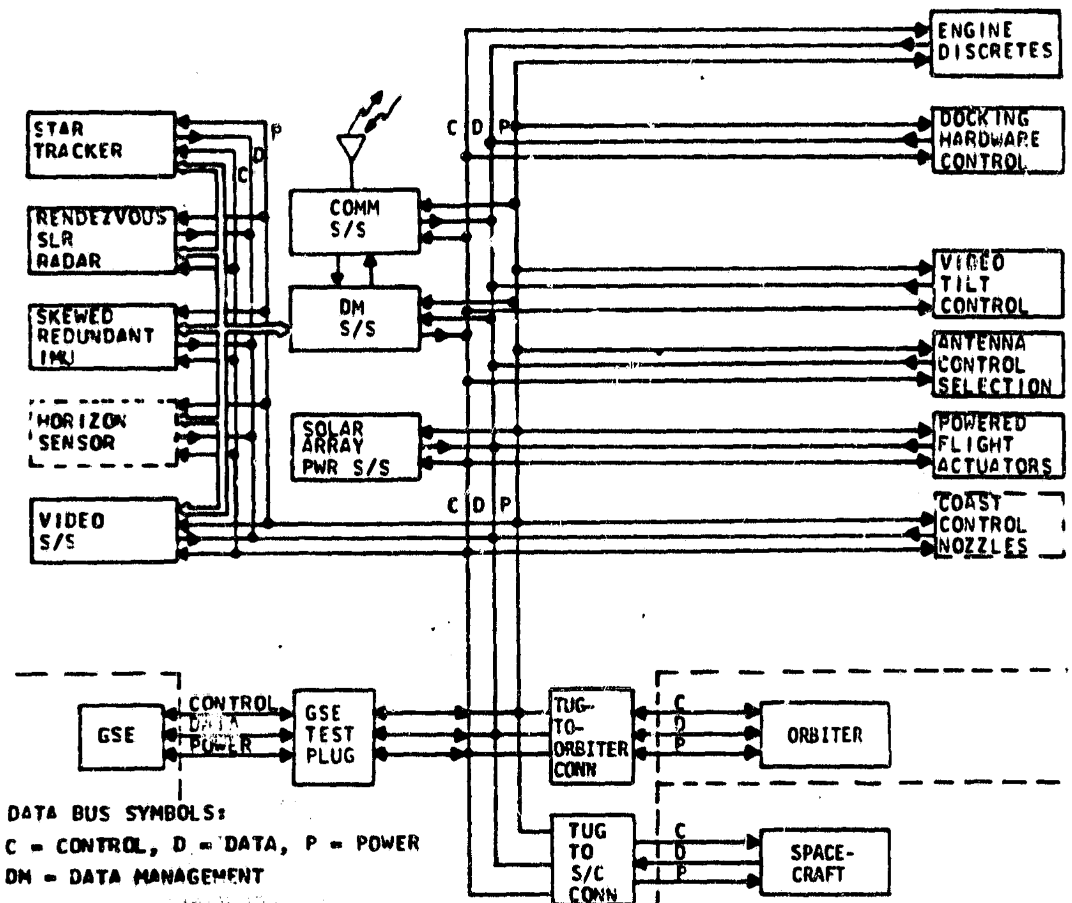


Fig. 2.2-5 Delivery/Retrieval Tug Avionics Subsystem, AV-2, Autonomy Level II

The vehicle control hardware and software are the same as those for Final Option 1 and will not be further discussed.

c. *Final Option 3* - This GN&C subsystem is a combination of those used for Final Options 1 and 2:

1) Final Option 3 1979 delivery-only Tug uses the Final Option 1 subsystem;

2) The Final Option 3 1983 delivery-only and delivery/retrieve Tugs use Final Option 2 subsystems.

d. *Final Option 3A* - This GN&C subsystem is the same as that for Final Option 3 except for certain minor software differences associated with the drop-tank staging sequence.

For a detailed functional description of the final selected GN&C subsystem, see Vol 5.0 of the *Selected Option Data Dump* (Ref 5.8).

2.2.4 Data Management Subsystem - This section discusses the study effort relative to the Tug data management subsystem (DMS), which provides the on-board digital logic-service functions of on-board checkout, redundancy control, data transfer, command decoding/distribution, data sampling/conditioning/accumulating/storage, caution and warning, timing, interstage/vehicle data transfer, coding/decoding, and computer services.

Major DMS considerations throughout all study phases were:

1) The need to limit intersubsystem permutations to minimize potential program costs;

2) The need for a very adaptive DMS capable of rapid reprogramming and checkout.

3) The need for a relatively large memory.

2.2.4.1 Requirements - The primary ground rules, requirements, and assumptions used for the DMS analysis were:

1) Provide sufficient on-board computation and memory storage to accommodate the worst-case DOD autonomous spacecraft retrieval missions;

2) Accommodate status data to, and command override control from, Orbiter-to-Tug parameters and functions that affect crew safety, including a caution and warning function;

3) Allow cost-effective checkout of Tug functions compatible with NASA launch processing system (LPS) and DOD satellite control facility (SCF) interfaces;

4) Provide for ground or Orbiter-to-Tug real-time command at 2 kbps;

5) Provide 16-kbps telemetry to either space tracking and data network (STDN) or SCF ground stations;

6) Accommodate government-furnished encrypter/decrypter box for DOD missions;

7) Provide for spacecraft-to-Orbiter or spacecraft-to-ground data-transfer capability.

2.2.4.2 Candidates Considered - The three DMS alternative design concepts considered were central hub, intermediate bus, and flexible signal interface. The *central hub* type is subdivided into many subgroups, each with its own set of black boxes, interfacing circuits, and connector pins. Interfaces are based on a separate wire or set of wires for each discrete function served. Time-division multiplexing is used only for interfacing with the communications subsystem. This type is used on most launch vehicles.

The *intermediate bus* type is like the B-1 bomber "E-MUX" system. Time-division multiplexing is used to save overall length and weight of wire between the central processor(s) and remote multiplexing units. Interfaces to other subsystems, boxes, devices, and transducers are still on a "wire-per-function" basis from the remote multiplexers.

The *flexible signal interface* (FSI) type uses the same coding, timing, and circuitry as the intermediate bus DMS, except for one important item--the remote multiplexers are eliminated. The bus itself is run to every black box in the system, each of which has its own unique address. This process eliminates the "wire per function" of the intermediate bus DMS. The flexible signal interface approach permits standardization of all interfaces, resulting in a simplification of integration and testing.

2.2.4.3 Selection Methods - Methods used for subsystem selection were based on evaluation of candidates against absolute and relative criteria, with special emphasis on the effect on overall Tug and Shuttle program costs.

Absolute criteria are factors like GN&C computation capability, caution and warning, variable transmission and command capability, fast Tug/spacecraft turnaround and changeout time.

Examples of the relative criteria are the black-box cost of weight and power, redundancy adaptability, interface complexity, onboard checkout capability, GSE required, operational flexibility, and total costs.

2.2.4.4 Selected Subsystem Candidates - A list of airborne computers is provided in the "Matrix of Candidate Computers" in *Requirements Assessment Presentation* (Ref 5.3). The computers listed are all applicable to the central hub approach. However, with the exception of the Autonetics and CDC machines, they do not reflect state-of-the-art computer technology.

Further consideration of the three DMS subsystem candidates resulted in the conclusion that no existing candidate flight computer system was efficient; therefore, none were selected. Instead, a new system was proposed from off-the-shelf commercial integrated-circuit technology.

2.2.4.5 Final Option Definition - The flexible signal interface system was selected in final competition with the intermediate bus system; the central hub system was eliminated because of excessive cost and doubtful ability to meet the basic requirements.

The flexible signal interface DMS system was selected for all potential Tug configurations because of the following considerations:

1) Lower cost, weight, and power requirements;

2) Greater functional capability;

3) Simpler Tug/Orbiter, Tug/spacecraft and Tug/GSE interfaces;

4) Potential for large savings in overall Tug program costs;

5) Potential large savings in Orbiter crew size, interface hardware, interface software, and training required;

6) High adaptibility to progressive growth in Tug subsystem capability;

7) Permits some black-box checkout software to be used in flight and for between-flight maintenance checks as originally developed for breadboard and qualification tests.

Figure 2.2-6 illustrates the selected FSI DMS system. Significant characteristics are:

1) A central unit containing four 1-megabit solid-state random-access memories, four general-purpose central processors and two control, data, timing, and checkout (CDTC) processors.

2) Two duplicate sets (for redundancy) of control and data cabling--each set is a twisted shielded pair of 22-gage copper wire (eight conductors total);

3) A required number of branch circuit sets, each set made up of three hybrid circuits and one standard resistor pack;

4) Eight branch boxes;

5) One government-furnished encrypter/decrypter module.

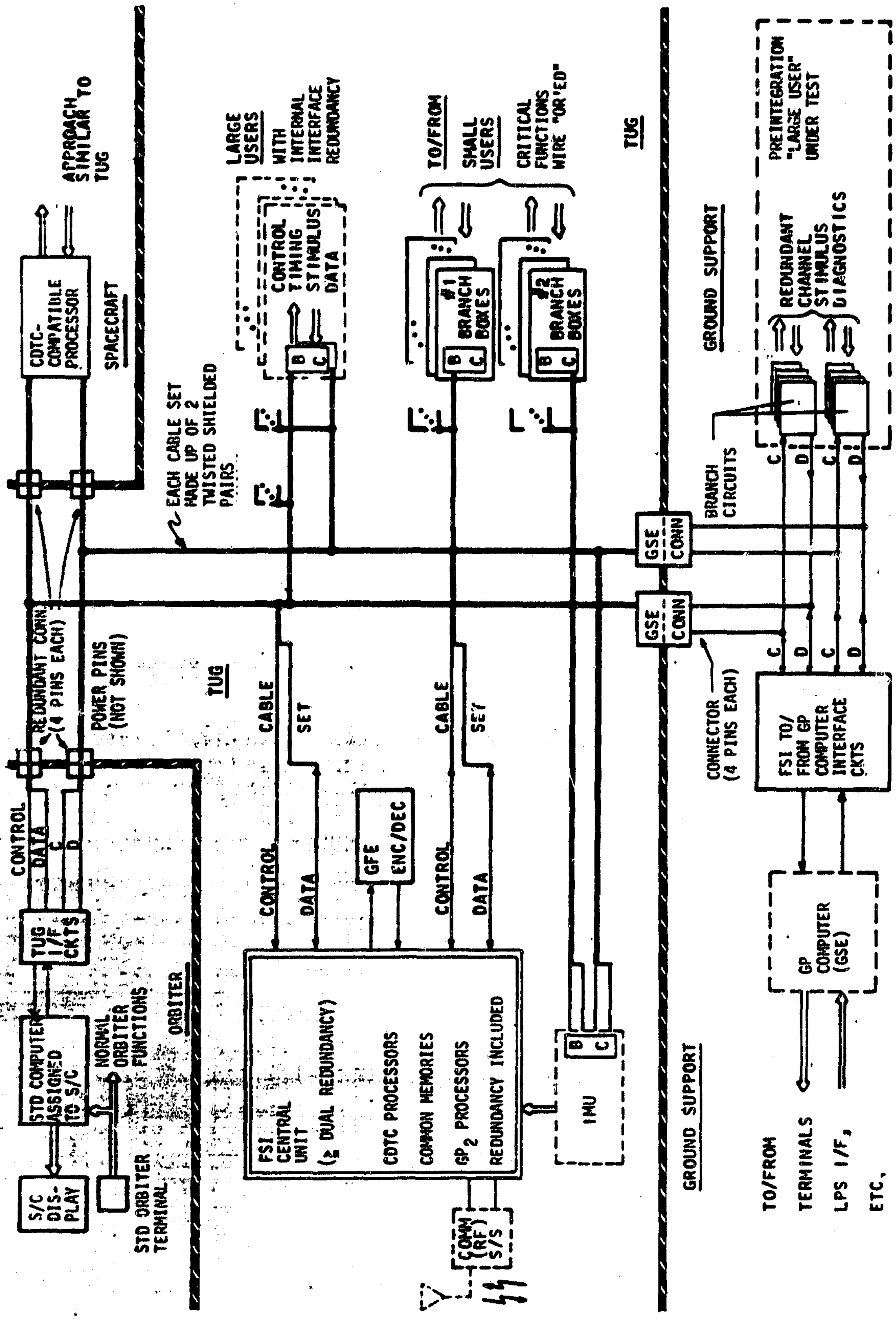


Fig. 2.2-6 Data Management Flexible Signal Interface Approach

Complete details of the functional capabilities and applications of this subsystem may be found in Vol 5.0, Sec. I, para 2.3.3.2.a.3 through 2.3.3.2.a.5 of the *Selected Option Data Dump* (Ref 5.8).

2.2.5 Communications Subsystem - This study effort was oriented toward a Tug subsystem that would satisfy RF interface requirements associated with the Orbiter, Tug payloads, the NASA Space Tracking and Data Network (STDN), the Air Force Satellite Control Facility (SCF) network, and the potential relay satellite. Conceptual designs of the candidate subsystems were developed in conjunction with the data management subsystem because of the close interrelationship of the principle subsystem requirements.

2.2.5.1 Requirements - Figure 2.2-7 illustrates the program RF and hardware interfaces that the Tug must serve. The following mission or mission-derived requirements were the driving factors in the initial subsystem conceptual designs:

1) Maintain compatibility with both STDN and SCF networks. A design goal established for this requirement was to use common hardware for both NASA and DOD missions to preclude changeout of equipment when a changeout of Tug or of Tug and spacecraft is required (10-hr turnaround);

2) Provide continuous monitoring and control communications between Tug and the NASA Mission Control Center. It was assumed that back-up capability was also required by the Satellite Test Center (STC) on DOD missions;

3) Provide for two-way RF links between the Orbiter and Tug for deployment, rendezvous, and docking operations, with emphasis on the caution and warning requirements;

4) Maintain compatibility with Tug payload communications subsystems to enhance Tug recovery of spacecraft whose communication system is still operable, but with its capability limited to short intervals while passing over a compatible ground system.

It was further assumed that the spacecraft would be able to transmit a few channels of sampled kick-stage data to verify proper operation without implementing an additional communications subsystem similar in cost and weight to that used on Tug. This interface would be used for kick-stage operations, following deployment separation from the Tug.

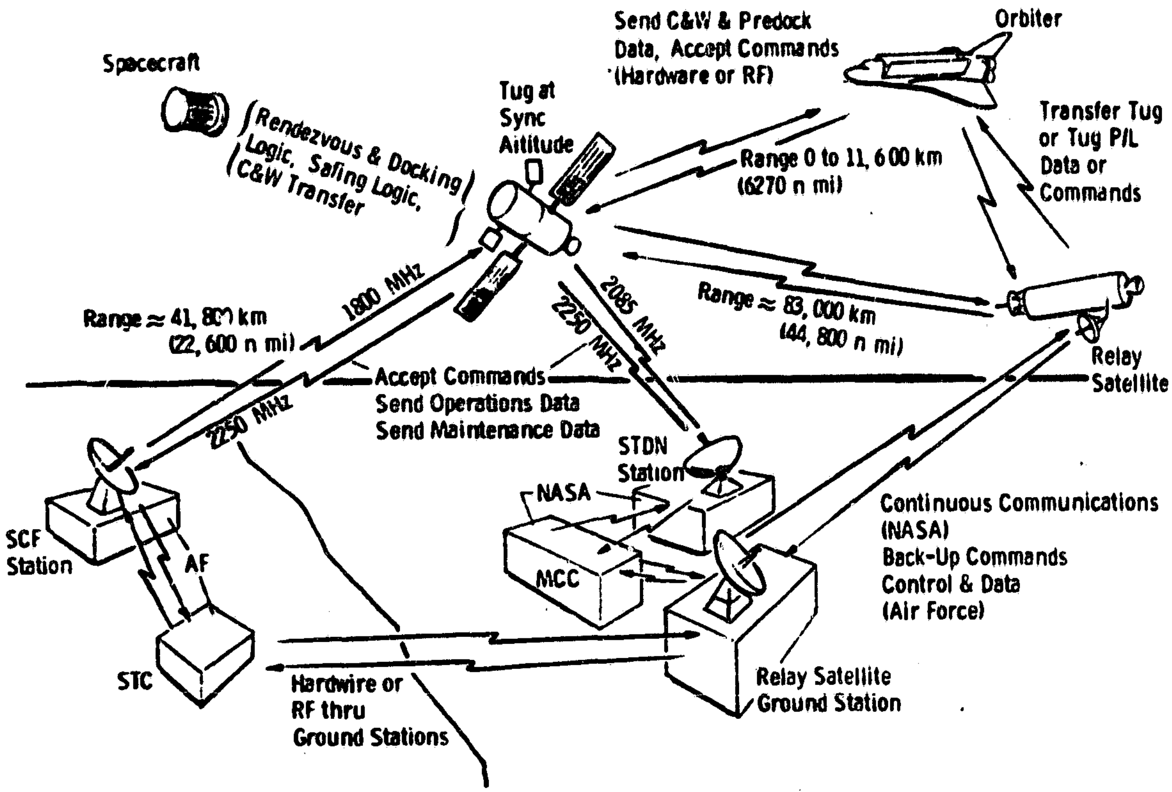


Fig. 2.2-7 Communications Subsystem Program Interfaces

2.2.5.2 <u>Candidates Considered</u> - There were two primary subsystem candidates considered.

1) The first concept was a compatible mix of separate hardware subsystems, which included:

   (a) 2250-MHZ downlink transmitter for frequency compatibility between Tug and Orbiter, STDN, or SCF;

   (b) 1800-MHZ command receivers compatible with Orbiter or SCF;

   (c) 2075-MHZ command receivers for STDN;

   (d) 136-to-148-MHZ transmitter and receiver sets for Orbiter interface on NASA missions;

   (e) 13,700-MHZ (K_u-band) transmitter for communication with a proposed NASA GSFC communications satellite for altitudes up to 2700 n mi (5000 km)--the limit of satellite antenna coverage;

(f) Omnidirectional and VHF antennas;

(g) High-gain gimbaled K_u-band parabolic antenna;

(h) 15,000-MHZ command receiver for interface with the Tracking and Data Relay Satellite (TDRS) under 2700 n mi (5000 km);

(i) Equipment (TBD) for accommodating continuous Tug/control center communication while above 2700 n mi (5000 km).

2) The second concept considered was a dual-redundant S-band subsystem including the following components:

(a) 2250-MHZ low-wattage transmitters;

(b) S-band amplifiers for Tug-to-relay-satellite link;

(c) Dual-channel command receivers (both SCF- and STDN-compatible);

(d) High-gain pointable antennas for the Tug/relay satellite link;

(e) Omnidirectional antenna for normal "close-in" Orbiter/Tug and some ground communications (particularly emergency command function);

(f) Implied compatible service from a relay satellite (to be negotiated);

(g) Implied compatibility with standard Orbiter hardware (to be determined).

2.2.5.3 Selection Methods - The method used for subsystem selection was to establish valid selection criteria, tradeoff the candidates against the criteria, and evaluate the results of this analysis before making the selection. Like the data management subsystem, the communication subsystem selected is applicable to all candidate Tug configurations.

The selection criteria applied include the following:

1) Demonstrated functional capability;

2) Low development cost and minimum technological risk;

3) Minimum weight;

4) High transmitter bulk to RF power-conversion efficiency;

5) Receiver sensitivity;

6) High operational life and high reliability;

7) Simple high-gain antenna with minimum effect on structural design;

8) Operational flexibility.

2.2.5.4 Selected Subsystem Candidates - Both the "mix" and the all S-Band subsystem design concepts were retained for Tug configuration synthesis in Task 3.

2.2.5.5 Final Option Definition - The all-S-band subsystem was selected over the "mix" subsystem because of the following considerations:

1) Lower nonrecurring and recurring costs;

2) Lower weight;

3) Least effect on Tug structure design;

4) Capable of meeting all operational requirements;

5) Permits total program communications subsystem cost reduction by logical planning to preclude the high cost and weight penalties that result from multiple-frequency-band designs (Tug, Tug payloads, Orbiter, relay satellite).

Figure 2.2-8 shows the all-S-band communication subsystem. Hybrid branch-circuit data-management interface piece parts would be incorporated into the coupling and switching network as well as into each high-gain antenna gimbal-drive electronics module. The transmitters and power amplifiers are off-the-shelf items. The high-gain antennas are flat planar arrays that provide for simpler fabrication, less structural design effects on Tug, and lower weight than a parabolic reflector. The multifeed wrap-around omnidirectional antenna reduces the effects of appendages on antenna gain patterns and provides better roll-axis patterns (fewer deep nulls) than dipoles. The low-power 2-W transmitter, plus separate switchable 10-W amplifiers, permit selectivity of operating modes, reducing RF power requirements. Figure 2.2-9 further illustrates the many different modes with which the Tug can interface with the Orbiter.

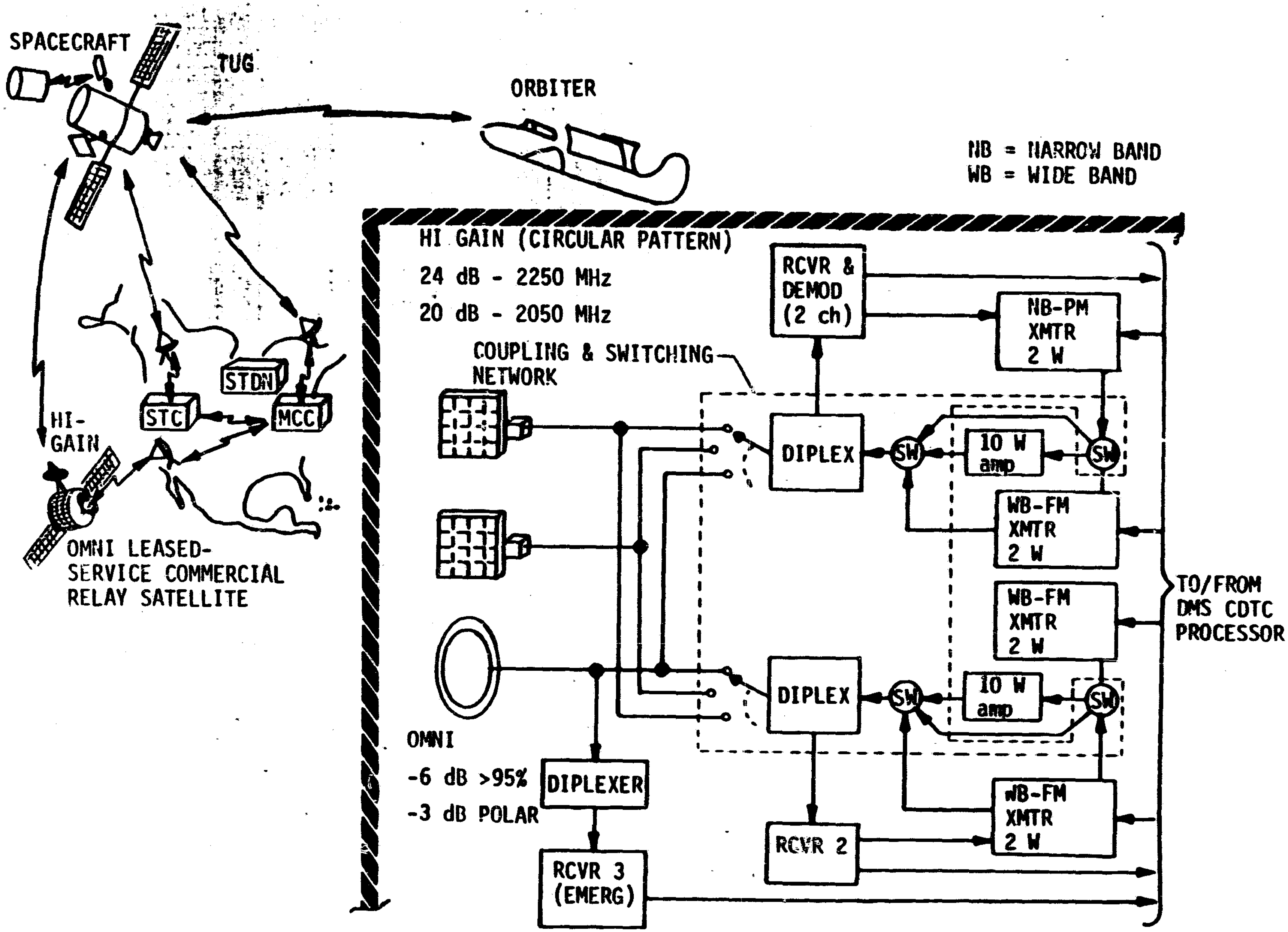
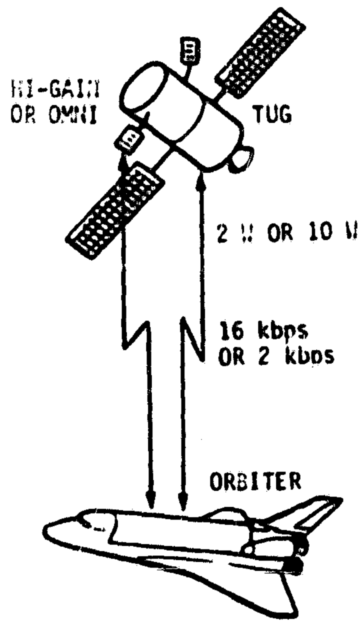


Fig. 2.2-8 Tug Communications Subsystem



TUG/ORBITER MODE		
TUG CONFIG	RANGE	
	n mi	km
2 W + OMNI + 16 kbps	31	58
10 W + OMNI + 16 kbps	69	127
2 W + HI GAIN + 16 kbps	990	1,830
10 W + OMNI + 16 kbps	2220	4,100
2 W + OMNI + 2 kbsp	88	162
10 W + OMNI + 2 kbps	200	370
10 W + HI GAIN + 2 kbps	6270	11,600

Fig. 2.2-9 Tug/Orbiter S-Band-Link Mode Capability

A more detailed discussion of operational modes and communication link analyses is in Vol 5.0, Sec. I, para 2.3.3.2.c of the *Selected Option Data Dump* (Ref 5.8).

A candidate for further study would be the incorporation of convolutional coder and Viterbi decoder circuits to either enhance link performance or reduce RF power and/or antenna aperature size.

2.2.6 Electrical Power Subsystem

The following paragraphs describe the effort to reach the logical choice of a Tug electrical power subsystem for the final selected Tug options. The initial phase of the study was primarily concerned with comparison of all potential candidates to absolute and relative criteria, while the final phase consisted of a more detailed analysis and final selection of a subsystem that satisfied the particular missions defined in the final Tug options.

2.2.6.1 Requirements - Basic requirements for the electrical power subsystem are summarized in Table 2.2-3. The primary factors influencing the choice of the power source are the mission duration and electrical load. Mission durations analyzed in the study are 36 hr and 7 days. From the electrical load profiles

determined by analysis during the study, average power and total energy requirements for several mission types can be summarized as follows:

Mission	Average Power, W	Energy, kWh	Total Energy in Orbiter, kWh
36 hour Delivery Only	480	17.3	16.1
7 Day Delivery	671	96.7	16.1
Delivery & Retrieval	711	102.4	12.0

Table 2.2-3 Power Subsystem Requirements Summary

Mission Criteria:

Duration - 1 to 30 days outside Orbiter, 1-day max in Orbiter
Mission Type - Delivery Only, Delivery & Retrieval
Technology Level - IOC of 1979
Duration in Earth's Shadow - 2.3 hr max, 45 min operational worst case

Electrical Load: (see text)

Environment: Compatible with Shuttle & Tug environments

Interface:

Tug/Orbiter - Accept up to 50 kWh at nominal 28 Vdc, with following constraints:

1000 W avg & 1500 W peak during peak Orbiter operation period
3000 W avg & 6000 W peak during on-orbit coast periods

Tug/spacecraft - Power supplied to spacecraft, none for 36-hr mission, 300 W otherwise
Tug/GSE - As required for maintenance & checkout

Operation:

High degree of autonomous on-board power subsystem & load management
Capability to detect & isolate malfunctions & to switch to redundant functions
Capability for Orbiter/ground monitoring & control

Reuse and Refurbishment:

Minimize ground checkout, maintenance, & refurbishment/replacement
Minimize in-space checkout
Minimize maintenance, checkout, & operational costs
20 Tug reuses nominal, 100 reuses as a design goal

Reliability and Safety:

0.97 success probability (for total Tug vehicle-mission)
Prevent discharge of harmful contaminants

It was also determined that the total energy required depends on the "coast" operational mode (85-95%) and increases as the total mission time increases.

2.2.6.2 Candidates Considered - The electrical power subsystem consists of the power source, power conditioning equipment, and power distribution and control. The need for power conditioning devices is determined by the type of power source and the input voltage requirements of the individual piece of equipment. Because the equipment voltage requirement was 28 ±4 V in all cases and all power source alternatives, except for the solar-array system, can satisfy this voltage range by their inherent output characteristics, the power conditioning equipment trade-off was not a major effort.

Table 2.2-4 lists the power sources considered through Task 2.

Table 2.2-4 Power Source Candidates

Candidates	Types
Storage Battery	Ag-Zn, Ag-Cd, Ni-Cd, lithium, metal gas, sodium sulfur, molten salt electrolyte
Fuel Cell	Reactant: $H_2 - O_2$, hydrazine, hydrocarbon
	Reactant Storage: cryogenic, gaseous
Solar Array/Battery	Solar Array: body-mounted & Sun-oriented panel
	Battery: Ag-Zn, Ag-Cd, Ni-Cd, Lithium
Auxiliary Power Unit	$H_2 - O_2$, Hydrazine - O_2
Radioisotope	Fuel: Pu_{238}, Cu_{244}
	Converter: thermoelectric, Brayton, Rankine
Nuclear Reactor	Fuel: zirconium hydride
	Converter: thermoelectric, Brayton, Rankine

The power sources in the table collectively represent the level of technology available or predicted through 1990.

Power distribution techniques considered differ only in the number of redundant positive feeders and the use of wire or the vehicle structure for current return.

2.2.6.3 Selection Methods - The basic selection method used in Task 2 was to first screen out the undesirable candidates and then conduct a detailed comparison of the remaining alternatives. The primary factors applied in the initial screening procedure were availability, cost, weight, and technical risk. Secondary factors included performance, life, and reliability.

Some optimization was performed on a specific type of component or technique based on weight and performance considerations. For example, the fuel-cell candidates were either a Shuttle-developed type weighing about 125 lb (56.7 kg) or one that is lighter [≈50 lb (22.7 kg)] but with a higher DDT&E cost.

2.2.6.4 Selected Subsystem Candidates - Power source candidates remaining at the end of Task 2 were the H_2-O_2 fuel cell, solar array/Ag-Zn battery, and the Ag-Zn battery. Rejection logic for the other candidates is shown in Table 2.2-5.

Table 2.2-5 Rejected Power Sources

Sources	Reasons
Nuclear Systems	- Extremely high cost & weight - Fuel availability problems - Requires large volume - Radiation hazards, ground/abort safety problems - Large vehicle integration problems - Incompatible with manned Shuttle
Auxiliary Power Units, N_2H_4 or H_2O_2	- Used only for high power, short duration - High reactant consumption rates [5 to 6 lb (2.3 to 2.7 kg)/kWh for N_2H_4] - High weight - Requires extensive development
Ni-Cd & Ag-Cd Batteries	- Not weight competitive with Ag-Zn system
Na-S, Molten Salt Electrolyte & Organic Electrolyte Lithium Batteries; N_2H_4 & Hydrocarbon Fuel Cells	- Very low development state - High technical risk - High development cost

Final selection of Tug power sources during Task 3 was directed toward 36-hr and 7-day missions.

Based on cost for the 36-hr mission, which requires no power to the spacecraft, the all-battery system was the clear choice. The power source for the 7-day mission (300 W to spacecraft) was a choice between solar-array/battery and fuel-cell/battery systems. A trade study based on weight, cost, performance, operational complexity, refurbishment, test, checkout, and safety was performed. The results shown in Table 2.2-6 reveal the main differences to be in weight, cost, operational mode, test, and checkout. For weight consideration versus mission duration, Fig. 2.2-10 indicates that the fuel-cell system weight increases with a given mission duration due to additional reactants and tankage required, while also showing that the solar-array system weight is relatively insensitive to mission duration. The need to orient and extend/retract panels makes the solar-array system more complex operationally.

After careful evaluation, it was concluded that the solar-array system offered the least weight and the least overall program life-cycle cost, while providing the most flexible modularized subsystem.

Of the several types of solar-array system candidates considered, the final choice was the General Electric array, based on best specific weight density, simpler structural mounting interface, lighter weight, and preferred Sun-orientation mechanism.

2.2.6.5 <u>Final Option Definition</u> - Figure 2.2-11 shows the Final Option 1 battery power subsystem block diagram using four 165-Ah Ag-Zn batteries and one 25-Ah Ag-Zn battery for the 36-hr mission with no load to the spacecraft.

Figure 2.2-12 is a simplified block diagram of the Final Option 2, 3, and 3A solar-array/battery electrical subsystem, showing the solar array, batteries, chargers, load regulators, and power distributors. Auxiliary subsystems not shown are solar-array orientation and instrumentation. Power sources consist of two roll-up solar arrays of flexible Kapton substrate, one 165-Ah Ag-Zn and one 25-Ah Ag-Zn battery. The power distribution design using a two-wire-positive, wire-return system provides bus redundancy, detection and isolation of faults in power feeders, EMI protection, and load-control capability, and all critical control functions with command override capability by the Orbiter or ground control. The data management subsystem implements all monitoring and control functions, as well as on-board checkout of the power subsystem.

A more detailed analysis and functional description of the final selected electrical power subsystems may be found in Vol 5.0, Sect. I of the *Selected Option Data Dump* (Ref 5.8). A discussion of Tug/Orbiter electrical interfaces is in para 2.5.4 of this volume.

Table 2.2-6 Comparison of Solar-Array (SA) and Fuel-Cell (FC) Systems

Factors	Solar Array/Battery System	Fuel Cell System
Weight		
- Wt vs Mission Time	Insensitive to mission duration; wt lighter than fuel cell	Increases with mission duration; wt significantly higher with increasing mission duration
- ΔWt/Δ 100-W Load	≈0	≈ +0.144 lb (0.065 kg) for 6-day mission ≈ +0.72 lb (0.33 kg) for 30-day mission
Performance	Continuous / Peak	Continuous / Peak
- Bus Pwr Output Capability	One SA Sys: 0.7 kW / 2.9 kW Two SA Sys: 1.7 kW / 4.4 kW	One FC Sys: 0.7 W / 1500 W Two FC Sys: 0.7 W / 3000 W
- Input Pwr Required	≈60 W (pwr dist control & array orientation)	≈100 W (FC and cryo heaters)
- Environmental Degradation	8% per yr in sync orbit	Negligible
- Contamination	SA outgassing negligible	H_2O, H_2 & O_2
- Operational Life (estimate only)	5 to 10 yr with minor replacement (solar-cell modules, slip ring, actuators)	- Up to 6 mo on fuel cell stack (complete replacement required) - Up to 1 year on cryo tanks - Plumbing up to 1 year
Cost		
- DDT&E	\$1.3 million	\$3.34 million
- 1st Article	\$0.5 million (1 set)	\$0.41 million (1 set)
- Avg Cost/Vehicle	\$0.823 million*	\$0.60 million*
- GSE	Minimal	Very high
Operational Complexity		
- Orientation Requirement	2-axis, computer controlled	None
- Constraints	SA must be retracted during main engine burns, operation in or near Orbiter, & docking & undocking with spacecraft	Gas & water dumping must be controlled
- Orbiter & GSE Interface	Electrical only	Electrical & fluid (for LH_2, LO_2, & pressure relief); special GSE for LO_2 & LH_2 required
Refurbishment	Replacement of SA assy simple & easy	Replacement of FC stack, cyro tanks, & plumbing difficult
Maintenance	None required	FC & cryo systems requires pressurization during storage, extensive leak checks, & special GSE
Test & Checkout	Minimal, no delay or extension of integrated system tests	Dedicated maintenance & checkout time required at launch site
Safety	No major problems	Special handling for pressure vessels, LO_2 & LH_2

*2 Solar-array assemblies & 2 regulators; 2 fuel-cell powerplants & 2 sets of cryogenic tanks.

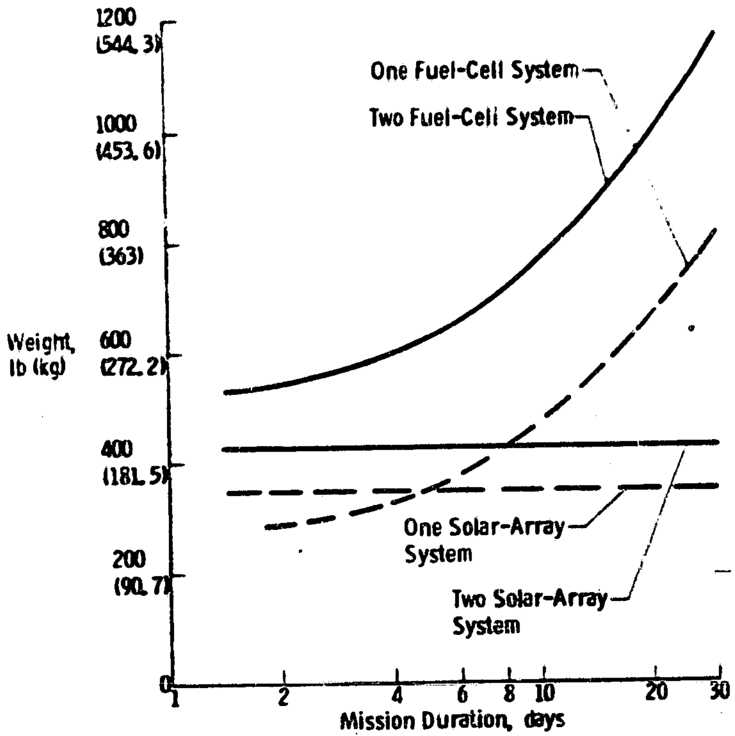


Fig. 2.2-10 Total Launch Weight vs Required Mission Duration

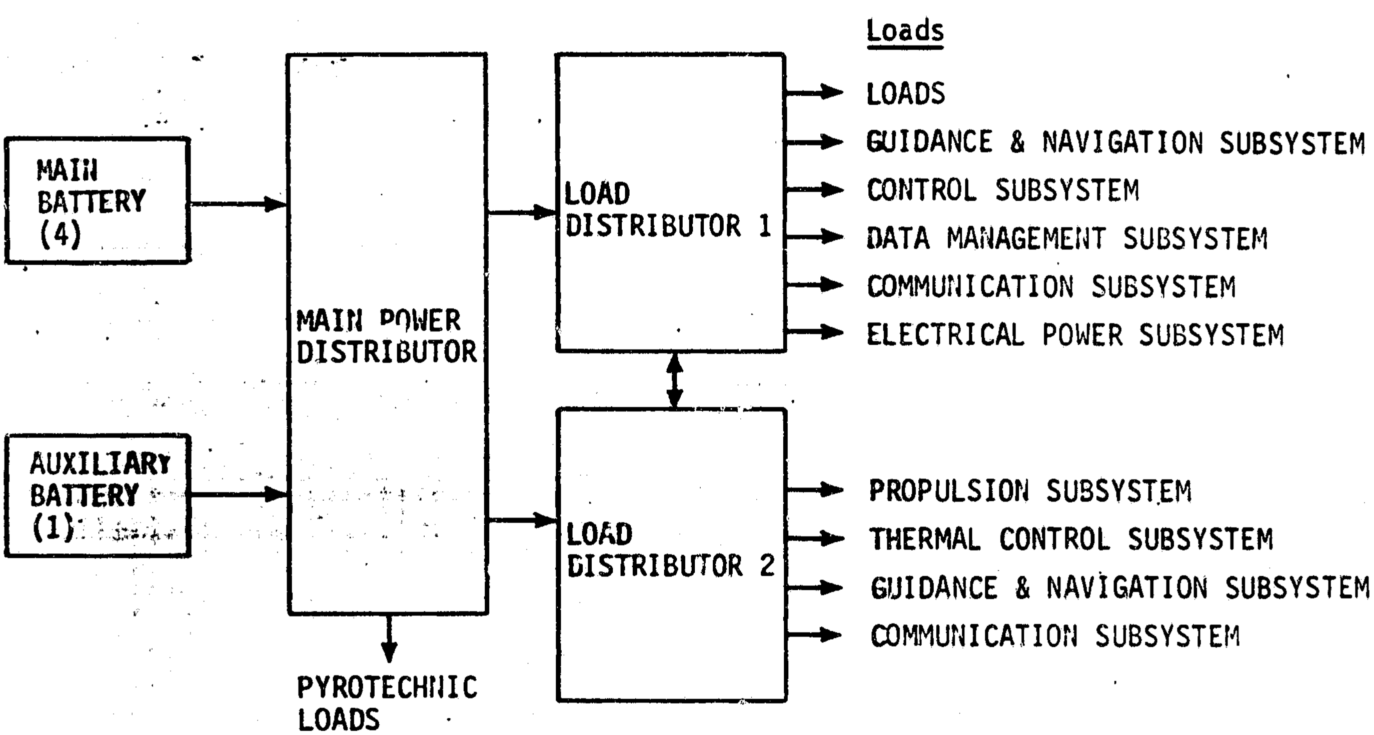


Fig. 2.2-11 Simplified Block Diagram of Power Subsystem for Final Option 1

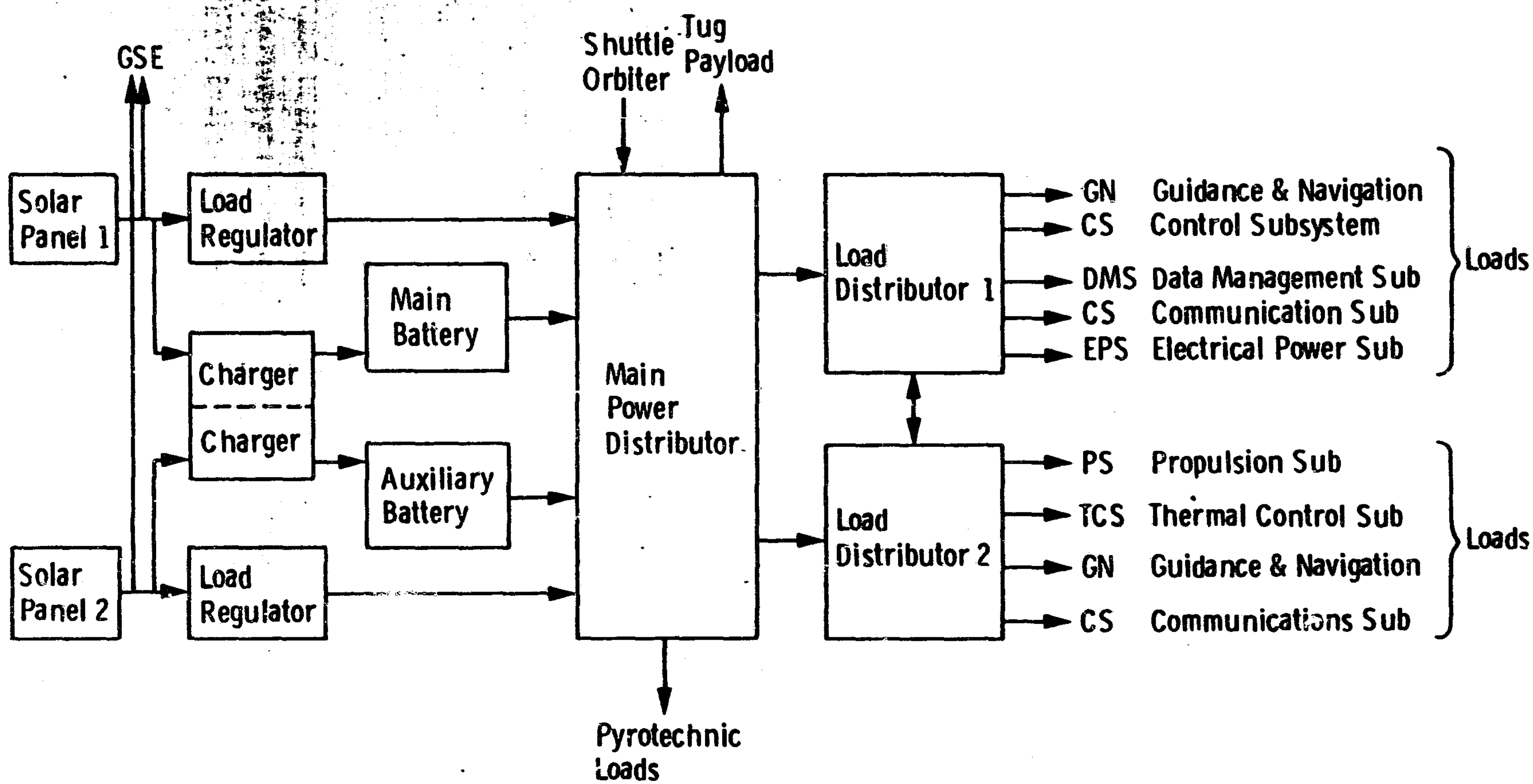


Fig. 2.2-12 Solar-Array/Battery-Power Subsystem Block Diagram

2.2.7 Main Propulsion Subsystem

The main propulsion system requirements, candidates considered and selected, and rationale are summarized in the following paragraphs. A more detailed evaluation covering each final option is in Vol 5.0 of the *Selected Option Data Dump* (Ref 5.8).

2.2.7.1 Requirements - There are a number of ground rules, assumptions, and requirements affecting design and selection of the propulsion subsystem. In general, the ground rules were taken from the *Data Package Space Tug System Studies* (Ref 5.12), and the propulsion requirements were derived from the mission requirements.

Assumptions were made where ground rules or other study information was not available. If the effects of the assumptions were significant in subsystem or major component selection, this was identified to the customer for resolution and agreement, or presented in the form of a trade study. Low cost, simplicity, high reliability, and ease of maintenance tempered with good engineering judgement were used in the design and selection of each subsystem. Some of the more significant requirements are:

1) The propulsion system shall be designed to be fail safe;

2) Relief capability to automatically limit maximum pressure shall be provided for pressurized propellant tanks;

3) Reuseability life of 20 missions with a design goal of 100 missions;

4) Propellant isolation valves shall be provided upstream of engine start valves;

5) Provisions shall be made to permit emergency offloading of Tug propellants while the Tug is stowed in the Orbiter cargo bay on the launch pad;

6) The main propulsion subsystem shall meet the derived mission requirements of Table 2.2-7;

7) The main engine thrust level shall be such that the spacecraft g level shall not exceed 3.6.

Table 2.2-7 Space Tug Requirements Derived from Mission Requirements

Item	Interim Tug	Direct-Developed & Evolved Tugs
Mission Duration (max)	3 days	7 days (30-day goal)
Number of Main Propulsive Burns (max)	10	10 (12 goal)
Launch-to-Deployment Time (min/max)	0.9-10 hr (24 hr spec)	Same
Launch-to-First-Burn Time (min/max)	1.3 to 30.0 hr	1.3 to 5.0 days (28-day goal)
Time Between Main Burns (min/max)	0.2 to 18 hr	0.2 to 72 hr (28-day goal)
Near-Earth Coast Time Outside Orbiter Bay (min/max)	0.5 to 5 hr	0.5 hr to 7.0 days (30-day goal)
Operational Altitude (min/max)	100 to 100,000 n mi (185.2 to 185,200 km)	100 to 100,000 n mi (185.2 to 185,200 km)
Number Midcourse/Vernier Burns (won't exceed)	10	20
ΔV for Midcourse/Vernier Burns (min/max) 1) Shutdown Impulse Dispersion 2) Minimum Impulse Bit	Derived from main engines: 1) $\pm 3\sigma$ = 750 lb-sec (3336 N-s) 2) 8000 lb-sec (35,586 N-s)	Same/~15 fps* (~4.57 m/s)
Continuous Sunlight Time (min/max)	0.9 to 60 hr	0.9 hr to 5.0 days (28-day goal)
Continuous Shadow Time (min/max)	0.6 to 2.3 hr	0.6 to 2.3 hr
Mission Mode	Delivery/return empty	Deliver/Retrieve
Propellant/Burn (max)	33,000 lb (14,969 kg)	33,000 lb (14,969 kg)
*Spacecraft contamination on retrieval consideration.		

2.2.7.2 Candidates Considered and Selection Methods

2.2.7.2.1 Propellant Selection - Fuel candidates considered for the Tug were UDMH, N_2H_4, A-50, and MMH. Of these, when considered with N_2O_4 oxidizer, UDMH has the lowest performance and N_2H_4 the highest. However, N_2H_4 is undesirable because of its heat sensitivity and freezing point. The two favored candidates thus become A-50 and MMH. Parameters also considered included vapor pressure, viscosity, heat of vaporization, explosive limits in air, flash points in an open cup, and cost.

The performance of MMH and A-50 with N_2O_4 is very nearly the same. A-50 has a lower cost; however, there are definite technical advantages of MMH over A-50--most are related to engine design and operation. MMH has a lower freezing point, superior thermal stability, and greater cooling capacity, compared to A-50. These parameters and commonality with the Orbiter OMS and RCS led to the selection of MMH during subsystem analysis.

It is anticipated that propellant temperatures will be maintained at 70°F (21°C) or below; however, the system is designed to accommodate 80°F (27°C). The 80°F (27°C) temperature was established based on Titan vehicle historical records at both ETR and WTR.

2.2.7.2.2 Main Engine Candidates - Main engine candidates considered for the Tug are listed in Table 2.2-8, along with some preliminary weighting factors. Engines that showed the best potential for Tug application based on a cost versus performance evaluation are noted by asterisks. Prime engine candidates recommended were the OME 12,000-lb (53,379-N) thrust, 240 P_c, and the Class I, 1500°F (816°C) wall high-P_c engine. Other contenders were the Bell Aerospace 8096B and the OME 7500-lb (33,362-N) thrust, 150 P_c for a minimum DDT&E cost option. The maximum capability of a storable propellant engine for Tug is shown as the Class II, 3000°F (1649°C) wall high-P_c engine.

A significant parameter affecting main-engine thrust level and selection is the requirement not to exceed 3.6 g on the spacecraft. Considering this requirement, as well as optimizing thrust level by considering velocity losses, engine I_{sp}, vehicle effects, and engine weight decrease with thrust level resulted in the optimum selected thrust level of 12,000 lb (53,379 N).

At the *Program Concept Evaluation* (Ref 5.5), comparisons between OME deviations and the 8096B engine did not show either engine as clearly a better choice, although the OME seemed to have a slight advantage. The OME was then selected over the 8096B for the detailed stage evaluation in Task 5.

At the 28 August 1973 engine-contractors' engine data dump, Bell Aerospace recommended a constant thrust level of approximately 12,000-lb (53,379-N) for the 8096B by modifying the chamber nozzle throat to a smaller size. By maintaining the same engine length, the expansion ratio was increased, resulting in an increase in specific impulse of approximately 4.5 sec (44.13 N-sec/kg). Based on the revised data, the Bell 8096B now appears to be the most performance/cost-effective engine candidate from a

subsystem standpoint without consideration of total Space Transportation System programmatics. These data were presented as a sensitivity study in the *Selected Option Data Dump* (Ref 5.8) and are summarized in para 2.4.3.6 of this report.

Table 2.2-8 Candidate Engines (Initial Evaluation)

Engine	Thrust, lb (N)	I_{sp}, s (N-s/kg)	Area Ratio	Mixture Ratio	DDT&E, $M
New, Class I, 1500°F* (816°C)	12,000 (53,379)	337.6 (3310.7)	300	2.0	59
New, Class I, 3000°F (1649°C)	12,000 (53,379)	339.5 (3329.3)	300	2.0	74
New, Class II, 1500°F (816°C)	12,000 (53,379)	340.8 (3342.1)	400	2.0	109
New, Class II, 3000°F* (1649°C)	12,000 (53,379)	344.4 (3377.4)	400	2.0	124
Bell 8096	17,340 (77,132)	309.5 (3035.2)	200	2.69	21
Bell 8096A	16,000 (71,172)	319.0 (3128.3)	200	2.36	26
Bell 8096B*	16,000 (71,172)	329.6 (3232.3)	200	1.78	34
Bell 8096B-1	16,000 (71,172)	329.8 (3234.2)	200	1.61	34
OME 125 P_c	6,250 (27,801)	325.0 (3187.2)	200	1.65	24
OME 150 P_c*	7,500 (33,362)	325.0 (3187.2)	200	2.0	24
OME 240 P_c*	12,000 (53,379)	332.0 (3255.8)	200	2.0	34

*Selected candidate.

Studies after the *Selected Option Data Dump* again evaluated the main engine candidates for Final Option 3 (Phase-Developed Tug) based on total programmatics (performance, mission capture, fleet size, Shuttle flights, cost, etc). This resulted in selection of the Class I engine. The study evaluated the OME 240 P_c, Class I, and 8096B-2, both phasing and not phasing the engines. The rationale to examine the phasing of engines was to minimize peak funding requirements early in the Shuttle program. However, the

phasing of engines actually increased peak-year funding in approximately the sixth year (1981) because of the second engine development combining with peak production costs. This was presented in Vol 5.0, Sect. II, pages 6-5 through 6-7 of the *Selected Option Data Dump* (Ref 5.8).

When comparing the Class I engine to the OME 240 P_c and 8096B-2, the increase in DDT&E cost is more than compensated for by the reduction in Tug fleet size (two fewer expendables) and number of Shuttle flights due to the improved Class I performance. This study is summarized in para 3.0, "Additional Analysis," of this report.

2.2.7.2.3 Pressurization System Candidates - The baseline pressurization system was a regulated helium ambient storage with titanium sphere. This system was traded against eight other propellant tank pressurization techniques. The trade study summarized in Table 2.2-9 was a preliminary analysis assuming tank pressure level requirements of 17.5 psia (12.07 N/cm^2) in the fuel tank and 35 psia (24.13 N/cm^2) in the oxidizer tank. Results of the study eliminated four of the systems during subsystem analysis; however, several systems were retained for further evaluation based on the potential weight savings, as indicated in Table 2.2-9. As the study progressed, addition of engine-mounted boost pumps reduced oxidizer pressure to 28 psia (19.3 N/cm^2). The reduced pressure lowered pressurization system requirements and eliminated the weight advantage of the more sophisticated candidates. This eliminated all but the simplest and most reliable ambient stored helium system using composite materials for the helium sphere.

The Tug propellant-tank operating pressure levels were established by engine inlet requirements, pressure head required to overcome feedline friction, propellant vapor pressure, and the pressure bands necessary for proper tank pressure control and relief.

2.2.7.2.4 Propellant Feed System

2.2.7.2.4.1 Propellant Acquisition - The propellant acquisition subsystem must provide gas-free liquid to the engine for all short and long firings of the multiburn Tug missions. Propellant acquisition and retention concepts traded were settling thrusters against propellant retention devices. Propellant retention devices fall into three basic categories; i.e., active trap, screen surface-tension trap, and combined active and screen. Both the active trap and the combined active and screen devices have high maintenance and limited reuse problems. At the first review, both surface tension devices and settling thrust were still under investigation. Further study indicated that the surface tension trap

Table 2.2-9 Tug Pressurization Systems

Rating / System Type	Absolute Criteria: Approx Weight, lb (kg)	Maintenance & Reuse*	Safety*	Propellant Dump Capability	Relative Criteria: Approx Cost: Recurring Dollars, $K	Approx Cost: Nonrecurring	Reliability*	Complexity*	Checkout*	Previous Usage	Development Risk*	Remarks	Selected
Regulated He Ambient Storage (Baseline)	240 (109) Comp -43 (-20)	1	1	Yes	134	1	2	2	3	Apollo Transtg Delta Agena	1	- Max Tank Design Pressures	Yes
Regulated He Supercritical Storage	-97 (-44)	2	2	Limited	211	3	3	3	4	Apollo DPS	3	- Heat Exchanger Req - 30-day Life - Pad Loading - Duty-Cycle Dependent	Yes
Regulated He Cascade	-70 (-32)	2	2	Limited	269	3	3	3	4	Devel Tested	3	- Heat Exchanger Req - Pad Loading - Duty-Cycle Dependent	Yes
Autogenous	-36 (-16)	5	1	No [-94 lb (-43 kg) P/L for Dump]	166	2	2	2	2	Titan Centaur Saturn	1	- Gas Generator Req - Limited Restart - Fuel Tank Contamination	No
Dedicated Gas Generator	-7 (-3)	3	2	Yes	225	4	3	4	2	—	3	- Min Tank Design Pressures - Large Hydrazine Propellant Req - Negligible Weight Gain	No
Dedicated Gas Generator Cascade	-88 (-40)	3	2	Yes	297	4	4	4	4	—	3	- Operational Flexibility - Pad Loading	Yes
Dedicated Gas Generator Ambient He	-35 (-16) Comp -26 (-12)	2	2	Yes	207	2	3	3	3	—	2	- Operational Flexibility	Yes
He Blowdown	+295 (+134)	1	1	Yes	16 plus Tanks	1	1	1	1	Titan II	1	- Large Heavy Tanks Req	No
Main Tank Injection	-140 (-64)	5	3	Yes	230	5	3	3	3	Devel Tested	5	- Tank Contamination - Propellant Degration - Propellant Positioning	No

*Relative ratings — 1 thru 5, where 1 represents best rating & 5 poorest. No absolute value significance intended.

Comp – Composite Sphere

configuration was the most desirable propellant acquisition design for the reusable Tug. It showed a performance weight advantage over propellant settling, unlimited life characteristics with little or no maintenance, and it is efficient. Therefore, a refillable screen surface-tension trap configuration was selected.

2.2.7.2.4.2 Propellant Utilization and Gaging - Propellant outage studies were conducted to determine the expected magnitude of residual propellants on Tug due to main propulsion system performance dispersions. All subsystem variables, including component tolerances, were evaluated, and mixture ratio deviations, both loaded and burned, with the resulting residuals were calculated.

Based on these analyses, propellant outages that result without a utilization system are 0.43% of the total usable propellants or 243 lb (110.2 kg) maximum.

With a utilization system consisting of point level sensors and integrator, it is estimated that the residual propellants can be as low as 0.30% of the total usable propellants. In addition, the propellant utilization system can compensate for propulsion-system component performance deviations and, allowing relaxation of component tolerances, thus improve reliability and reduce cost. For these reasons, a propellant utilization system was recommended at the First Review.

2.2.7.3 Selected Subsystem Candidates - The previous discussion outlined candidate subsystems and selection methods. Subsystems recommended for further evaluation at the First Review are summarized in Table 2.2-10. Further evaluation led to the final options as discussed below.

Table 2.2-10 Selected Subsystem Candidates

Main Engine
Candidates shown in Table 2.2-8
Pressurization
Regulated helium ambient storage (baseline)
Regulated helium ambient storage - composite sphere
Regulated helium supercritical storage
Regulated helium cascade
Dedicated gas-generator cascade
Dedicated gas-generator/ambient helium
Propellant Feed
Propellants - N_2O_4/MMH
Propellant Acquisition—
Surface-tension device
Settling thrust
Propellant utilization system recommended

2.2.7.4 Final Option Definition - Because the emphasis in Final Option 1 was to minimize DDT&E cost, the engine selected was the OME, uprated to 150-psia (103.4-N/cm^2) chamber pressure by addition of engine-mounted boost pumps. Although the other engine options offer improved performance, the OME 150-P_c engine was the minimum-cost (DDT&E) engine option that still met the required performance of 3500-lb (1588-kg) delivery to geostationary orbit.

Due to the retrieval requirement of 3500 lb (1588 kg) the engine selected for Final Option 2 was the Class I engine. A sensitivity study was conducted on the use of the Class II engine for this option and is discussed in para 2.4.2.6, "Sensitivity Studies."

For Final Option 3, the *Selected Option Data Dump* (Ref 5.8) reflects the phasing of engines from the OME 240-P_c to the Class I. Subsequent analysis concluded that using the Class I engine in both the Phased Tug-Initial and Phased Tug-Final, not only reduced DDT&E cost and peak year funding but also Tug fleet size when compared to the OME 240-P_c or 8096B-2. This analysis is summarized in para 3.0, "Addition Analysis."

The basic propulsion schematic for single-stage vehicles is shown in Fig. 2.2-13. The pressurization subsystem of the main engine support is a regulated helium system consisting of a single pressurant sphere, hand-operated helium loading valve, capped helium disconnect, four solenoid valves, four regulators, two check valves, two self-sealing capped disconnects, and appropriate lines. The propellant tanks are protected from overpressure by burst/relief valves, one for the fuel tank and one for the oxidizer. Each is vented into its respective umbilical at the Tug/cradle interface.

The propellant delivery portion consists of two propellant acquisition devices—one fuel and one oxidizer—two propellant shutoff valves, two quadruple redundant propellant vent valves, and appropriate feedlines.

Propellant dump capability is provided in both the horizontal and vertical position. Horizontal fuel dump is through a 1-in. (2.54-cm) valve on the barrel section of the tank, a 1-in. (2.54-cm) line to a 2.5-in. (6.35-cm) line and valve at the aft end of the vehicle, which then goes to the fuel umbilical disconnect. Horizontal oxidizer dump is through a 1-in. (2.54-cm) valve on the barrel section of the tank, a 1-in. (2.54-cm) line to a 3-in. (7.62-cm) line and valve at the aft end of the vehicle that then goes to the oxidizer umbilical disconnect.

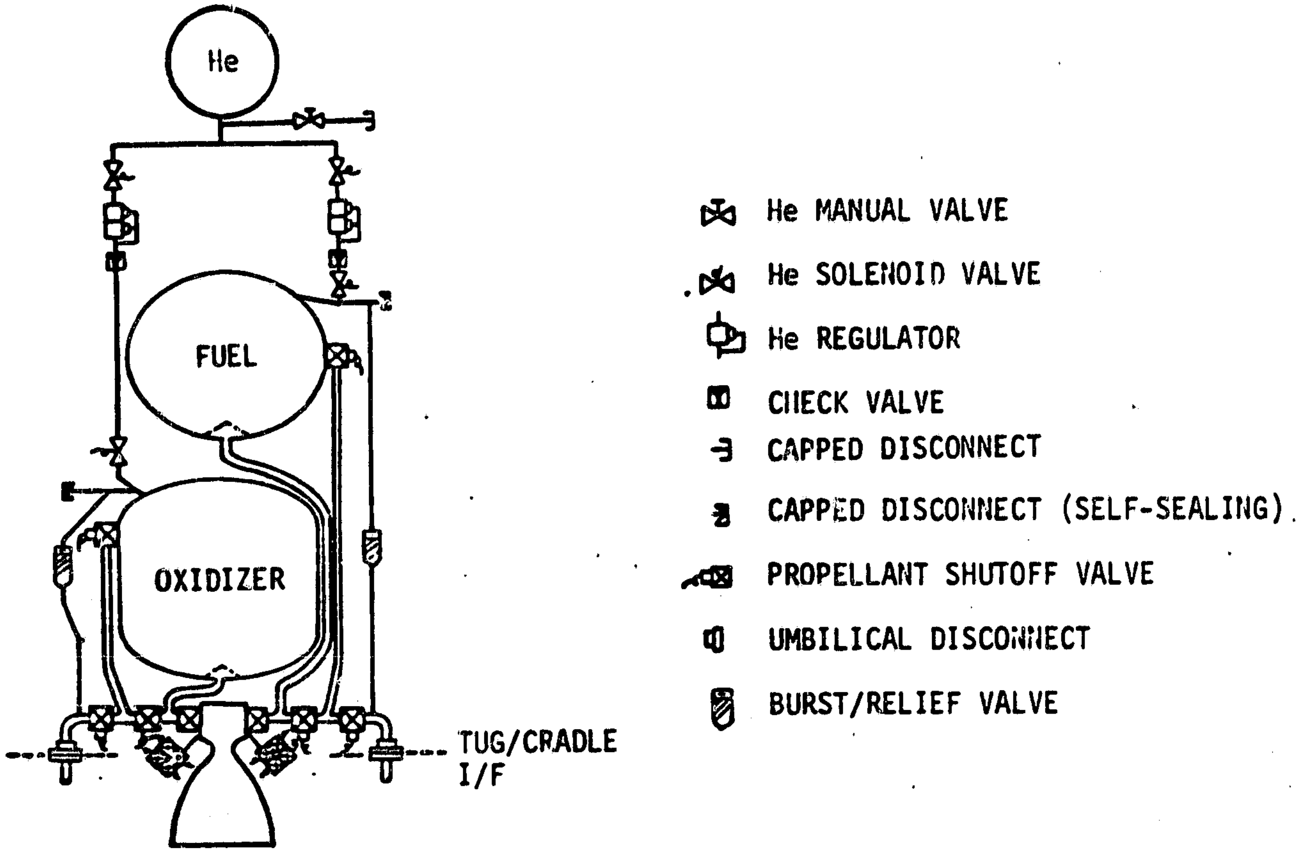


Fig. 2.2-13 Block Diagram of Tug Regulated Helium, Ambient Storage Configuration

Vertical dump is through the main propellant feed lines to a tee. The fluid then passes through a pair of valves--2.5 in. (6.35 cm) for fuel or 3 in. (7.62 cm) for oxidizer, to the Tug/cradle interface connector. The two valves provide series propellant isolation during all phases of the mission, including main engine operation. Propellant loading takes place before installation of the Tug in the Orbiter bay. Propellants are loaded through the dump system at the Tug/cradle umbilical connector.

The propellant dump philosophy during ascent abort is to dump during powered flight above 150,000 ft (45,720 m). This period was selected because it provides the highest beneficial g, eliminates possible dump-flow/boundary-layer interaction, and will not produce a change in center of gravity during Orbiter glide-back.

For Final Option 3A, the stage-and-a-half vehicle, the pressurization system schematic is the same as Fig. 2.2-13, and the propellant feed-system schematic is shown in Fig. 2.2-14.

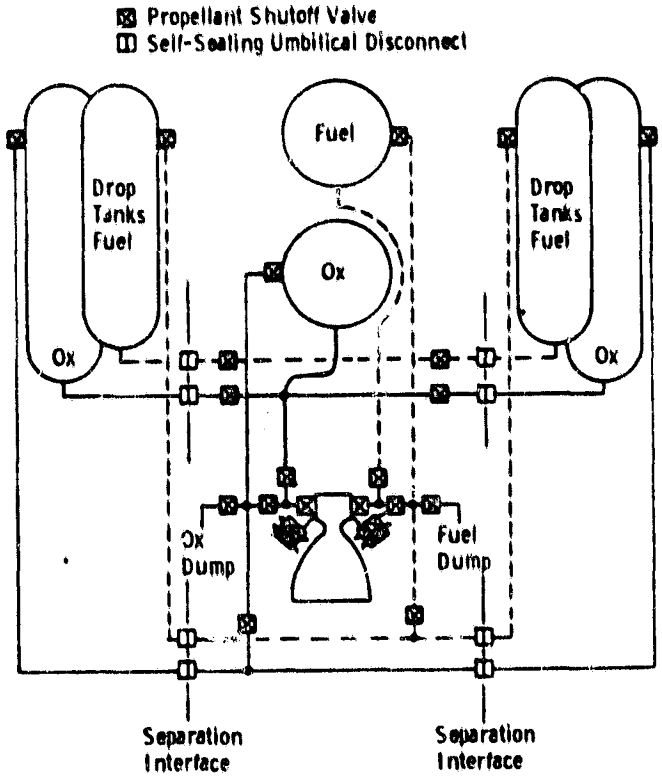


Fig. 2.2-14 Block Diagram of Tug Stage-and-a-Half Propellant Feed and Dump System

In operation, propellants first feed from the multiple drop tanks. When empty, these four tanks are jettisoned, and the engine is fed from the smaller core tanks. Switchover occurs between engine burns. The drop-tank concept is inherently more complicated and requires additional hardware in the propellant feed and pressurization subsystems.

The four tanks are pressurized using two separate subsystems that are expendable with the tanks. One subsystem services each set of oxidizer and fuel tanks on either side of the main core stage. A third reusable system pressurizes the core tanks. On all three systems, redundant series regulators are incorporated for mission assurance.

The propellant feed components include added feed-line disconnects and valves necessary to facilitate tank jettison. Wherever possible, these added components are mounted on and remain with the reusable main stage. Although the higher weights degrade the core mass fraction, attending performance penalties were accepted to minimize recurring hardware costs.

Core propellant tanks incorporate propellant retention devices similar to those for Final Options 1, 2, and 3. However, none are installed in the drop tanks. Studies indicated that, for the minimum number of engine starts required during drop-tank operation, propellant settling via the ACPS is more efficient. The drop-tank propellant gaging configuration uses a series of single-level sensors (not redundant) to minimize costs and weight. The core tank gaging is redundant.

As in other final options, propellants can be dumped in both horizontal and vertical positions from *all* main propellant tanks.

Performance and weight for each option is summarized in Table 2.2-11.

Table 2.2-11 Main Propulsion System Summary

	Final Option					
	1	2	3		3A	
Main Engine	OME 150	Class I	OME 240	Same As 2	Same As 3	
I_{sp}, s (N-s/kg)	327 (3,207)	338 (3,315)	330.3 (3,239)			
Thrust, lb (N)	7,500 (33,362)	12,000 (53,379)	12,000 (53,379)			
Wt, lb (kg)	330 (149.7)	268 (121.6)	398 (180.5)			
Propellant Quantity, lb (kg)	57,000 (25,855)	60,000 (27,216)			Core	Drop
MMH Fuel, lb (kg)	19,700 (8,936)	20,700 (9,389)	Same		4130 (1873)	16,550 (7,507)
N_2O_4 Oxidizer, lb (kg)	37,300 (16,919)	39,300 (17,827)			7870 (3570)	31,450 (14,265)
Main Engine Support						
Pressurization Reg He, lb (kg)	139 (63)	157 (71.2)	As		69 (31.3)	194 (88)
Propellant Feed, lb (kg)	45 (20.4)	45 (20.4)			85 (38.6)	56 (25.4)
Propellant Dump, lb (kg)	54 (24.5)	54 (24.5)			48 (21.8)	43 (19.5)
Propellant Acquisition, lb (kg)	30 (13.6)	30 (13.6)			30 (13.6)	10 (4.5)
Propellant Utilization, lb (kg)	30 (13.6)	30 (13.6)	2		24 (10.9)	36 (16.3)
Engine Actuators, lb (kg)	20 (9.1)	20 (9.1)			20 (9.1)	

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2.2.8 Auxiliary Control Propulsion Subsystem (ACPS)

ACPS requirements, candidates considered, candidates selected, and rationale are summarized in the following paragraphs. A more detailed evaluation of each final option is in Vol 5.0, Sect. II of the *Selected Option Data Dump* (Ref 5.8).

2.2.8.1 Requirements - As with main propulsion requirements, ground rules were generally taken from the *Data Package, Space Tug System Studies* (Ref 5.12), with the ACPS requirements derived from the mission requirements. Some of the more significant requirements are:

1) Designed to be fail-operational/fail-safe;

2) Capability of being shutdown by one command from the Orbiter;

3) Propellant isolation valves upstream from all engine start valves;

4) Relief capability to automatically limit maximum pressure in pressurized propellant tanks;

5) The Tug ACPS shall hold the angular rate and attitude position to the following accuracies for the coarse-hold and fine-hold operational modes:

	Coarse Mode	Fine Mode
Attitude (all axis), 3-σ	±5.0 deg (0.087 rad)	±0.5 deg (0.0087 rad)
Rate (all axis), 3-σ	±1.0 deg/s (0.017 rad/s)	±0.1 deg/s (0.0017 rad/s)

6) The Tug shall be capable of delivering spacecraft in a stable mode with the following velocity and tip-off rates maximum:

Longitudinal Velocity	5.0 fps (1.52 m/s)
Tip-off Rates	0.1 deg/s roll (0.0017 rad/s) 0.1 deg/s pitch and yaw (0.0017 rad/s)

7) The Tug ACPS shall be capable of maintaining Tug attitude and residual velocities during Orbiter retrieval of the Tug to the following accuracies:

Longitudinal Velocity	0.1 to 1.0 fps (0.0305 to 0.305 m/s)
Lateral Velocity	0.5 fps (0.152 m/s)
Angular Misalignment	±10 deg (0.174 rad)
Angular Rate	1.0 deg/s (0.017 rad/s)

8) Reusability life of 20 missions with a design goal of 100 missions;

9) Attitude control couples were assumed in all six rotational modes (North American Rockwell "Safety in Earth Orbit Study," (Ref 5.37);

10) Main-engine minimum impulse bit of 8000 lb-s (35,586 N-s);

11) Rotisserie assumed for spacecraft thermal control, with a "flip-flop" evaluated for worse-case propellant consumption;

12) Main-engine shutdown transient dispersion of $\pm 3\sigma = 750$ lb-sec (3336 N-s) assumed;

13) Application of fine-mode attitude hold for 2 hr maximum assumed;

14) Flight performance reserves of 10% assumed;

15) Tug/Orbiter separation of 1 mi (1.61 km) with ACPS assumed.

2.2.8.2 Candidates Considered/Selection Methods

2.2.8.2.1 ACPS Selection - Early in the Tug study, preliminary ACPS requirements indicated that total impulse ranged from 50,000 lb-sec (222,411 N-s) for attitude control to 300,000 lb-sec (1.334×10^6 N-s) for both attitude control and vernier maneuvers. Preliminary thruster size ranged from 15 lb (66.7 N) to 300 lb (1334 N) to accommodate both attitude control and vernier maneuvers. This range of impulse and thrust level led to consideration of both bipropellant and monopropellant systems. Low-thrust systems like monopropellant plenum, cold gas, bipropellant gas, subliming solids, etc, were not considered.

For the main propulsion system, an evaluation was performed on fuel candidates assuming N_2O_4 as the oxidizer. The candidates in order of preference were MMH, A-50, N_2H_4 and UDMH. Due to thruster availability and common propellant use with the OMS and Tug main propulsion systems, MMH was selected as the bipropellant fuel during the subsystem evaluation.

Monopropellants considered were hydrazine and hydrogen perioxide. Hydrazine was selected during the subsystem evaluation over hydrogen perioxide for its higher delivered specific impulse and improved storability. Hydrogen perioxide has the disadvantages of contamination sensitivity and slow decomposition during storage, requiring venting.

There are other monopropellants. However, they were not considered applicable to Tug for several reasons; one of which was no previous flight experience. These rejections included nitromethane, tetra nitromethane, ethylene oxide, and hydrazine/hydrazine nitrate.

The nozzle arrangement selected has 16 thrusters with four nozzles per quadrant, similar to that used on the Apollo service module. This arrangement provides control in all six degrees of freedom for complete Tug control during Orbiter separation, spacecraft release, and Orbiter retrieval of the Tug. With 16 thrusters, there is a one-engine-out capability, which is required to meet fail-operational/fail-safe criteria. Other nozzle arrangements were considered, as shown in Fig. 2.2-15; however, the system selected is the most efficient from the standpoint of total thrusters required, packaging, vehicle control, and one-engine-out capability.

Due to the large number of configurations being studied (single stage, two stage, etc) the total impulse requirement for the ACPS was not completely defined. Therefore, the performance relationship between monopropellant hydrazine and bipropellant systems with 16 thrusters was generated. The parametric charts of dry weight versus total impulse for the different systems are shown in Fig. 2.2-16. Each curve in this figure was generated using actual thruster weight data, as indicated.

A detailed evaluation of total impulse required was performed for the delivery-only mission and the delivery/retrieval mission (round trip). The analysis considered such items as Tug/Orbiter separation, spacecraft spin-up, inbound midcourse correction, attitude hold, and 10% performance reserves. The results of the analysis are indicated in Fig. 2.2-16, showing the rationale for selection of the Hydrazine system for all capability options during concept evaluation.

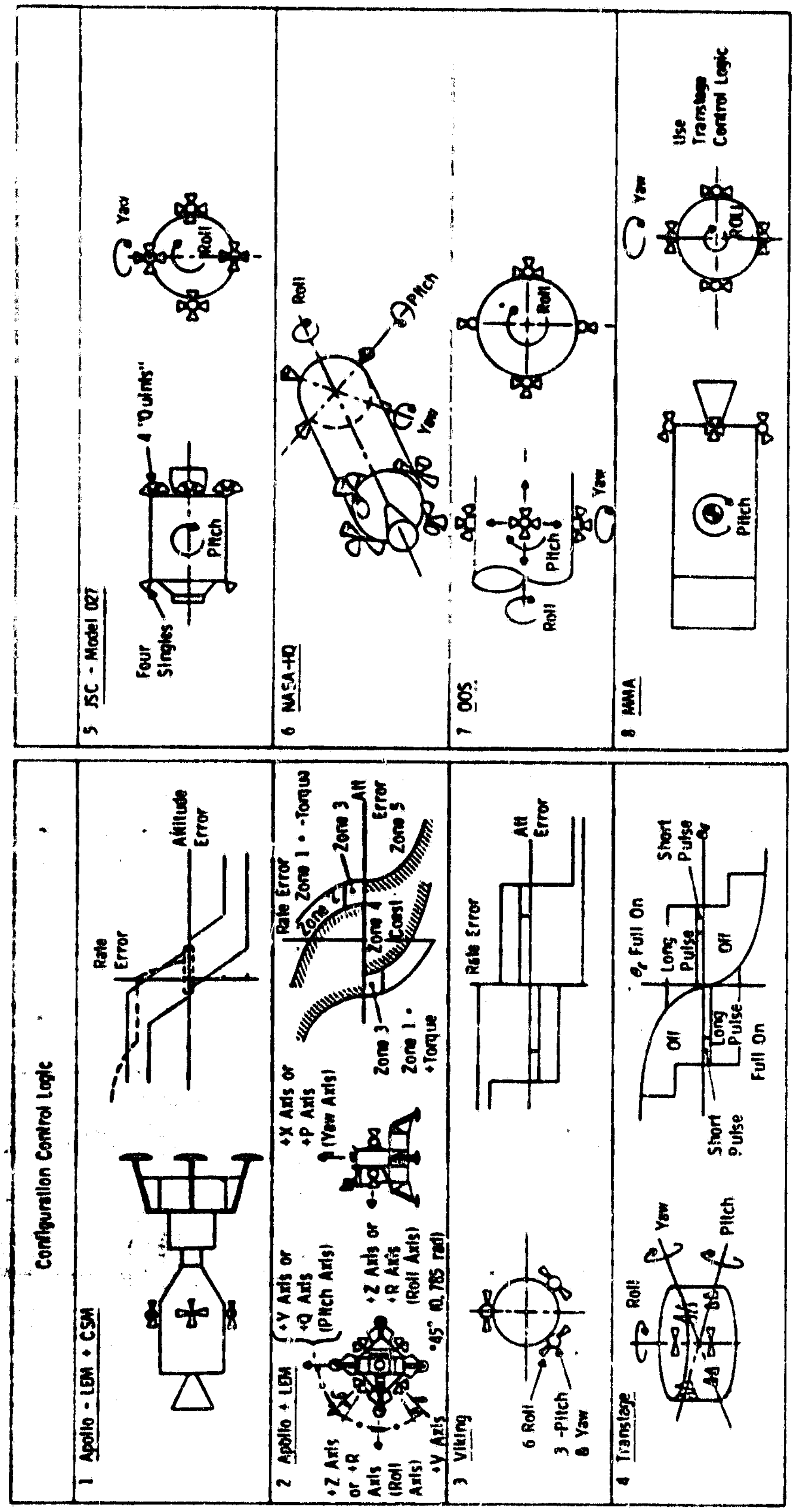

Fig. 2.2-15 ACPS Nozzle Arrangements Considered

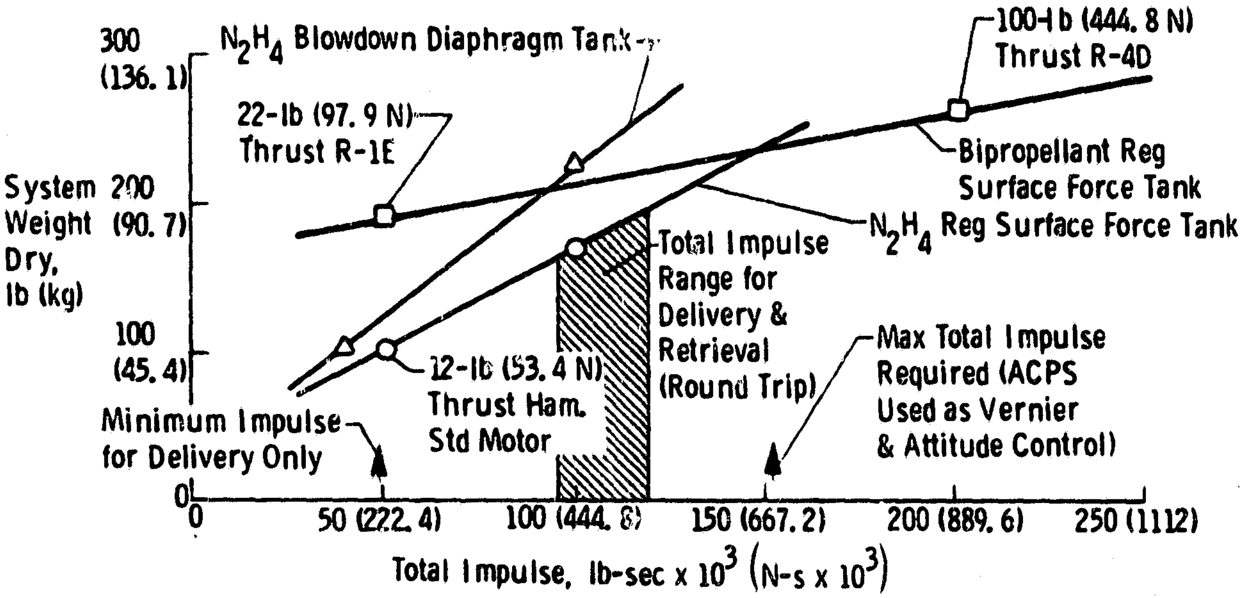

Fig. 2.2-16 Tug ACPS Selection

A significant parameter in determining the total ACPS impulse for a retrieval mission is the main-engine minimum impulse bit (MIB). With a small MIB, 8000 lb-s (35,586 N-s), part of the phasing ΔV for spacecraft retrieval can be performed with the main engine. If the ACPS were to perform all spacecraft phasing ΔV, total impulse would increase to the 153,000 lb-s (680,578 N-s) value shown in Fig. 2.2-16.

The bipropellant-versus-monopropellant crossover based on dry weight only is at approximately 150,000 lb-s (667,233 N-s), as shown in Fig. 2.2-16. The fact that monopropellant specific impulse is lower than that for a bipropellant requires more monopropellant for equivalent total impulse. This difference in propellant loaded cannot be compared directly to vehicle performance, but is a function of propellant use during the mission. Performing the analysis results in a lower crossover point at 130,000 lb-s (578,269 N-s).

Because of the large mass and inertia variation of the Tug with mission time, it is desirable to have high thrust levels initially to obtain adequate vehicle response. However, near mission completion, attitude hold requirements, both angular and position, combined with light mass and inertia, result in small minimum impulse bit. An evaluation of these parameters resulted in the selection of 25-lb (111.2-N) thrust nozzles. Optimum thrust in pitch and yaw was actually higher than 25 lb (111.2 N) and roll was lower; however, requirements in each axis can be met with 25-lb (111.2-N) thrusters, which allows a common engine to be used throughout the system.

2.2.8.2.2 ACPS Thruster Selection - Data were compiled and Tug candidate thrusters selected for both the bipropellant and monopropellant systems. Candidates comprised both existing and new development thrusters. Existing bipropellant candidates selected were the Marquardt R-1E, 22-lb (97.9-N) thrust engine and the Marquardt R-4D, 100-lb (444.8-N) thrust engine. They were selected for their high performance, low minimum impulse bit, demonstrated life, and qualification testing. The existing monopropellant candidate selected was the Rocket Research MR-3, 27-lb (120.1-N) thrust engine now flying on the Martin Marietta Transtage. Other candidates were the TRW MRE-50-73, 55-lb (244.6-N) thrust engine and the Hamilton Standard REA-22-4, 12-lb (53.4-N) thrust engine.

Because a monopropellant system was selected for Tug, a trade study was performed on the MR-3 thruster versus a new thruster with improved life. Results of the trade study showed the new thruster had a lower total program cost due to improved life. In addition, the new thruster can be optimized for thrust level as well as pulsing versus steady-state performance, depending on mission requirements.

Based on information available, a so-called vernier bipropellant engine of approximately 25-lb (111.2-N) thrust is proposed for the Orbiter. Assuming this engine could be used on the Tug at little or no DDT&E, a cost comparison was made between the monopropellant system selected with a new thruster and that with a bipropellant. The comparison did not indicate any driving cost advantage of the bipropellant system, even if the thruster could be obtained at a very low DDT&E cost to the Tug.

Because total impulse required for spacecraft retrieval is relatively large, a bipropellant vernier system was evaluated. The system consisted of an electric-motor pump assembly that draws propellant from the traps in the main propellant tanks and then feeds two thrusters. The vernier system would provide ΔV only, and a smaller monopropellant ACPS would provide attitude control and docking capability. The vernier system was then parametrically compared to an all-monopropellant system. Study results showed no vehicle weight or performance advantage of the vernier system; therefore, due to cost and system complexity, it was deleted from any further consideration.

An ACPS integrated with the main propulsion system was also considered. The system contains two electric-motor pump assemblies to meet fail-operation/fail-safe criteria. The pumps are required to boost pressure from the propellant tanks to approximately 300 psia (206.8 N/cm^2), where propellant accumulators would store up to 20,000 lb-s (88,964 N-s) of impulse for attitude hold to prevent running the pump continuously. The system weight of 249 lb (113 kg) is equivalent to an unintegrated bipropellant system with

approximately 200,000 lb-s (889,644 N-s) total impulse. Because Tug impulse requirements are lower, the integrated system was deleted from further consideration.

2.2.8.2.3 ACPS Propellant Management - There are several techniques for management and acquisition of propellants for the ACPS. For bipropellant systems, the most frequently used devices are Teflon bladders and metallic bellows. However, Teflon bladders have limited cycle life and metallic bellows tanks show a significant weight penalty. For hydrazine systems, nonmetallic bladder and diaphram tanks are generally used. Ethylene propylene rubber compounds are normally used with hydrazine to obtain better cycle life than Teflon; however, these rubber compounds have not been compatible with N_2O_4. Surface tension devices offer all the advantages of lightweight, reuse, minimum maintenance, and potential for unlimited life.

The surface tension device was selected by performing trade studies on tanks based on expulsion and volumetric efficiency, weight, off-load capability, cycle life, cost, and development risk.

2.2.8.3 Selected Subsystem Candidates - The previous discussion outlined candidate subsystems and selection methods. Subsystems recommended for further evaluation at the First Review were bipropellant and monopropellant hydrazine. These, selected thrusters, and the propellant management technique, are summarized in Table 2.2-12. Further evaluation led to the final options previously discussed.

Table 2.2-12 Selected Subsystem Candidates

ACPS System
Bipropellant - N_2O_4/MMH
Monopropellant - Hydrazine
Existing Thrusters
Bipropellant
Marquardt R-4D, 100-lb (444.8-N) Thrust
Marquardt R-1E, 22-lb (97.9-N) Thrust
Monopropellant
TRW MRE-50-73, 55-lb (244.6-N) Thrust
RRC MR-3A, 25-lb (111.2-N) Thrust
Hamilton Std REA-22-4, 12-lb (53.4-N) Thrust
Propellant Management
Bipropellant - Surface Force
Monopropellant - Surface Force & Diaphragm

2.2.8.4 Final Option Definition - For all final options, both single-stage and stage-and-a-half, a hydrazine monopropellant system was selected. The system shown in Fig. 2.2-17 has 16 thrusters arranged in four modules, with four thrusters per module. Each thruster is identical, with series-redundant thrust-chamber valves and a nominal thrust of 25 lb (111.2 N). The series valves were incorporated to prevent inadvertant thruster operation if a valve should fail in the open position.

The total impulse capability for Final Option 1 delivery-only is 62,500 lb-s (278,014 N-s), 300 lb (136 kg) of propellant. For Final Options 2, 3, and 3A the total impulse capability was increased to 125,000 lb-s (556,028 N-s), 600 lb (272 kg) of propellant, to accommodate spacecraft retrieval. In both cases, the total impulse capability is approximately 30% greater than that determined from the detailed ACPS propellant budgets. This increased capability was provided to cover all contingencies.

With the large difference in propellant requirements, two propellant tanks are proposed for Final Options 2, 3, and 3A; a large tank for retrieval and a small tank for delivery. A benefit of having two propellant tank sizes available, 300- and 600-lb (136- and 272-kg), is the 30-day servicing mission. For that mission, both propellant tanks would be flown, giving a 900-lb (408-kg) propellant capability compared to 834 lb (378.3 kg) required, based on a detailed analysis of the 30-day mission.

ACPS propellant acquisition is by a screen surface force device that is an integral part of the propellant tank. The propellant acquisition device for the ACPS must intermittently supply small quantities of propellant under the effect of an omnidirectional acceleration environment. This requirement is satisfied by channels that encircle the intertank wall. The tank is compartmented with capillary barriers to withstand high axial g levels resulting from vehicle rotations of up to 60 rpm. Compartmenting the tank also makes the device insensitive to propellant off-load.

The three-port two-way hand valve is used to isolate the propellant subsystem from the pressurization subsystem during ground servicing. Once the propellant and pressurization subsystems are serviced and checked, the hand valve is rotated to the free-flow or flight operational orientation and the service port capped.

The burst/relief valve on the propellant tank provides a burst disc for zero leak integrity, followed by a relief valve. Should a pressure surge rupture the burst disc, the relief valve will check tank pressure and prevent the potential loss of the Tug and mission. With this device, the tank is not only protected for safety considerations, but zero leakage is provided by the burst disc, as well as pressure check to maximize mission success.

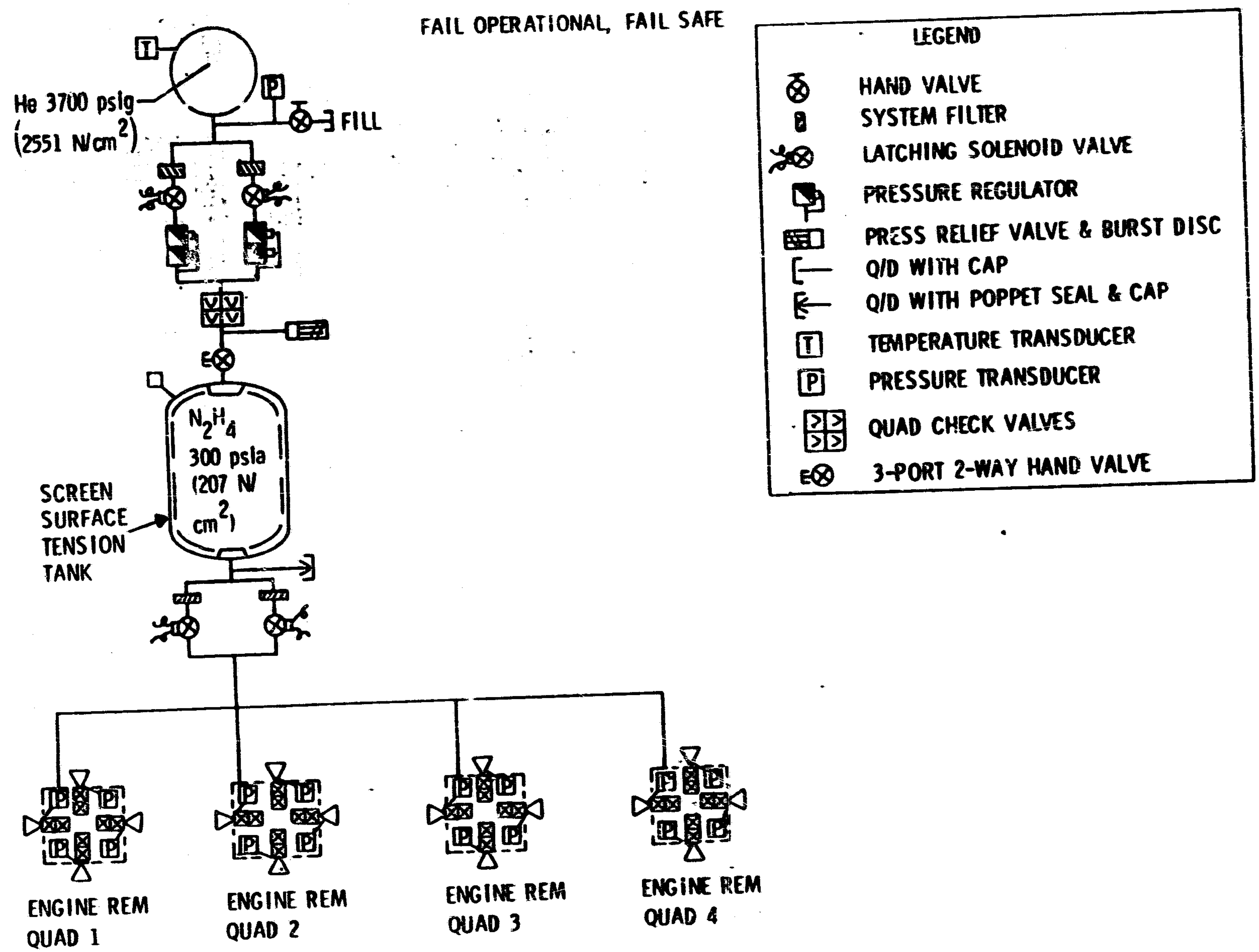

Fig. 2.2-17 Block Diagram of Hydrazine ACPS

Quadruple redundant check valves are provided downstream of the regulators to prevent potential vapors or liquid from contacting the pressure regulators.

The pressure regulators are series-redundant single-stage. Each is at a slightly different setting; thus, only one regulator is operating at any one time, which reduces the wear on the other regulators.

Latching solenoids are provided upstream of the regulators to isolate the high-pressure helium sphere and minimize time on the pressure regulators. For safety, these valves would remain closed on the ground and while the Tug is in the Orbiter.

2.2.9 Separation Module

2.2.9.1 Requirements - The separation module must provide the following.

1) Physical or structural tie between each of the following:

    (a) Tug and spacecraft;

    (b) Tug and kick-stage 10;

    (c) Tug and kick-stage 1.5;

    (d) Kick-stage 10 and kick-stage 1.5;

    (e) Kick-stage 10 and spacecraft;

    (f) Kick-stage 1.5 and spacecraft.

2) Electrical interface connection for the six combinations listed above.

3) Means of separating the six combinations listed above.

2.2.9.2 Configuration - The separation module shown in Fig. 2.2-18 is used on all 10-ft (3.05-m) dia vehicles, which include Final Options 1, 2, and 3. Final Option 3A is similar except the diameter is 6 ft (1.83 m). The baseline module is 10 ft (3.05 m) in diameter and 5 in. (12.7 cm) deep, made from 7075-T73 aluminum. It consists of two machined angles spliced with two notched frangible doublers with an oval stainless-steel tube in the splice. The angle flanges in each end of the 5-in. (12.7-cm) section bolt to the Tug and spacecraft, respectively, or any of the other five combinations listed in 2.2.9.1. Electrical disconnects are supported by brackets mounted on the outside wall of the module. Separation is achieved by detonating fuses inside the stainless tube, causing the frangible doublers to shear. After the doublers shear, final separation is achieved by springs in the module around its inside perimeter. Figure 2.2-19 shows the possible combinations of separation module.

2.2.10 Docking Module

2.2.10.1 Requirements - The docking module, which houses the docking mechanism, must provide for:

1) Delivering either a three-axis or spin-stabilized spacecraft;

2) Retrieving either a three-axis or spin-stabilized spacecraft;

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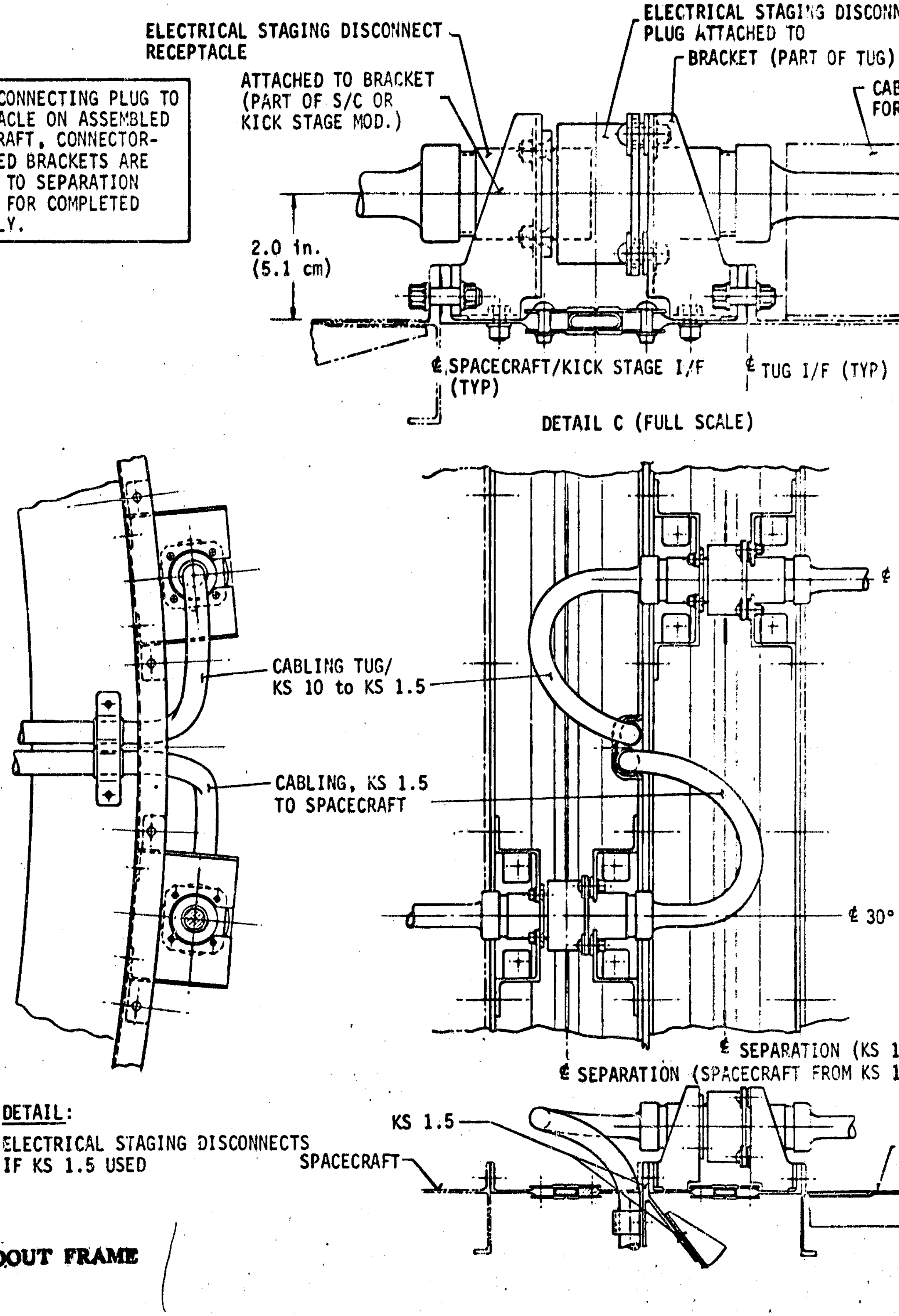
NOTE: AFTER CONNECTING PLUG TO RECEPTACLE ON ASSEMBLED SPACECRAFT, CONNECTOR-ATTACHED BRACKETS ARE BOLTED TO SEPARATION MODULE FOR COMPLETED ASSEMBLY.



DETAIL C (FULL SCALE)

DETAIL:

ELECTRICAL STAGING DISCONNECTS IF KS 1.5 USED

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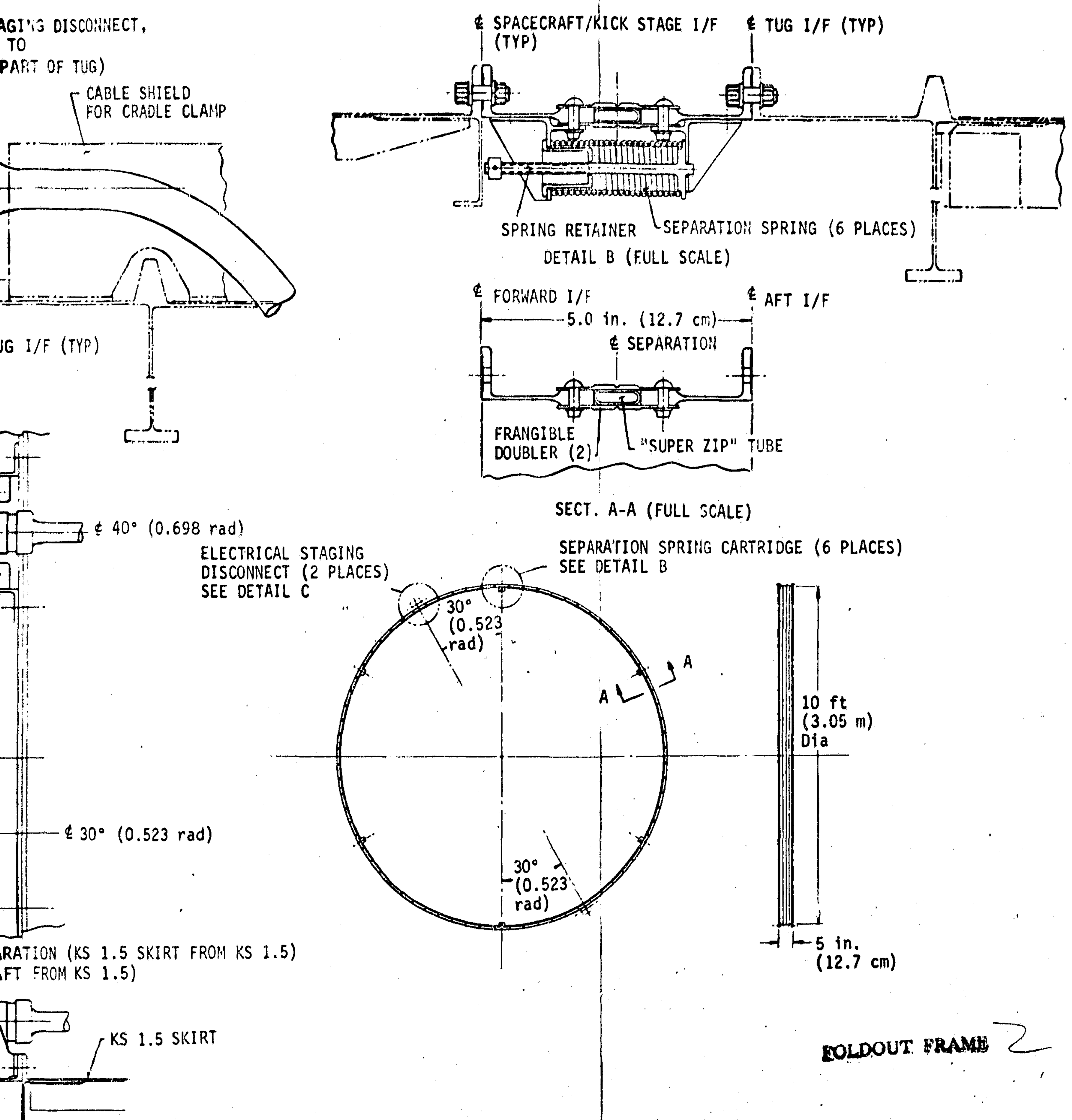

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Fig. 2.2-18 Separation Module

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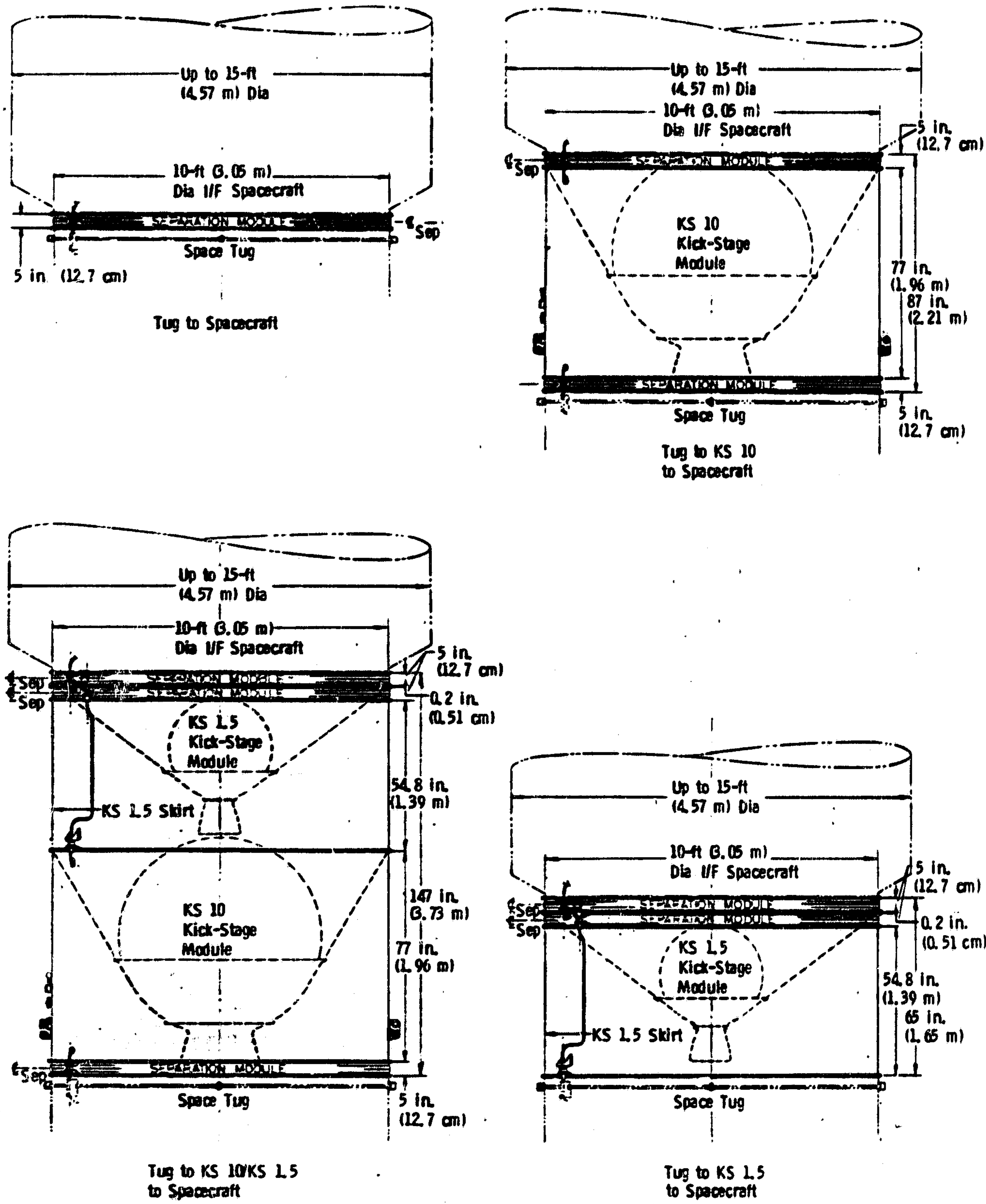


Fig. 2.2-19 Tug/Kick-Stage/Spacecraft Interface Arrangement

3) Docking under the following conditions:

   (a) Radial misalignment of ±6 in. (15.2 cm).

   (b) Angular misalignment of ±3 deg (0.052 rad)

   (c) Longitudinal velocity of 0.1 to 1.0 fps (0.03 to 0.3 m/s)

   (d) Lateral velocity of 0.30 fps (0.09 m/s)

   (e) Angular rate of 2.4 deg/s (0.041 rad/s)

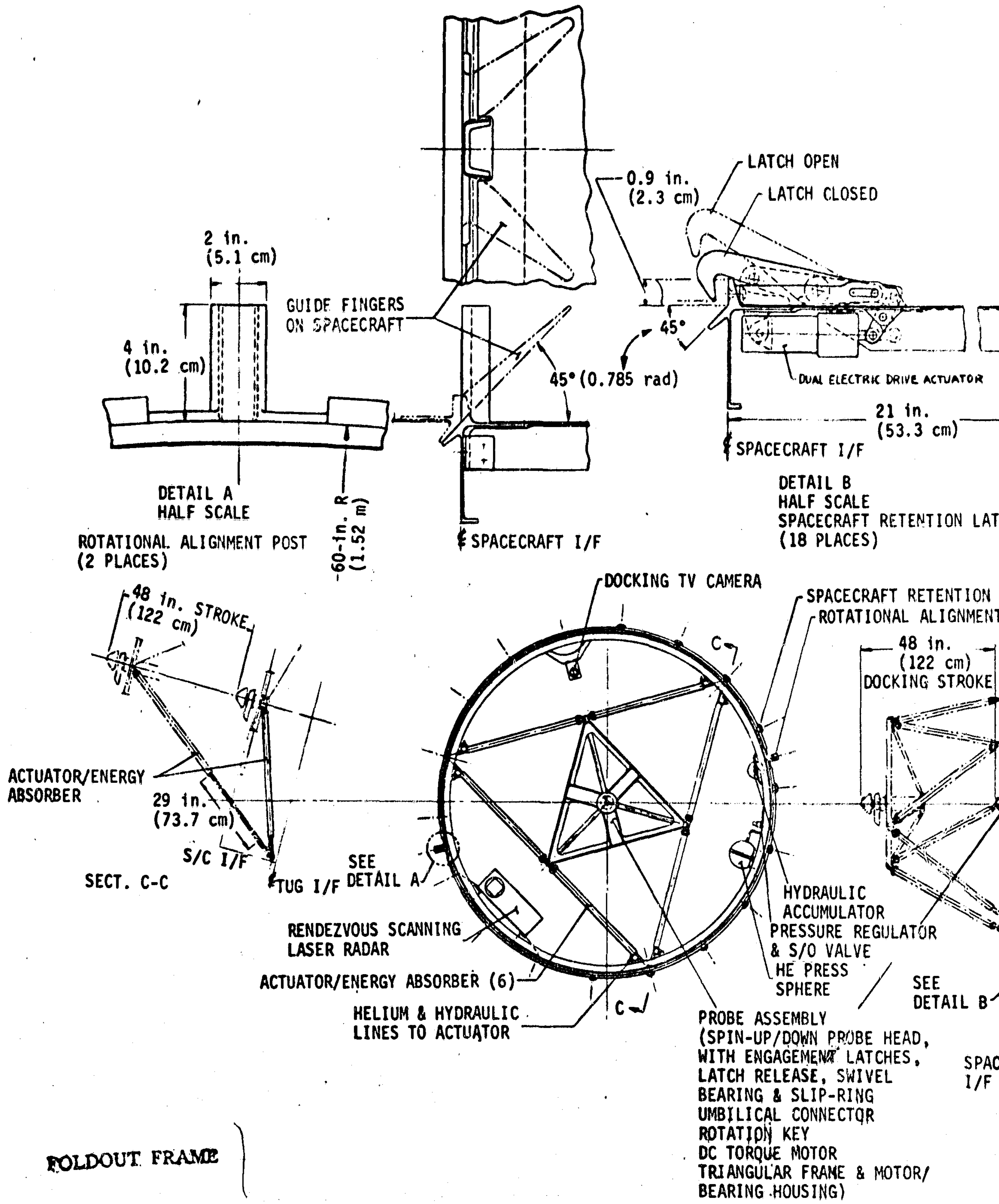
4) A structural latching system separate from the docking mechanism with sufficient strength and stiffness to support a spacecraft at all times except during the actual delivery or retrieval maneuvers.

5) An electrical interface connection to the spacecraft with disconnect capability at delivery but also capable of being reconnected at docking.

2.2.10.2 Configuration - As shown in Fig. 2.2-20, the docking module, is used on all 10-ft (3.05-m) dia vehicles that have docking capability. It consists of a 10-ft (3.05-m) dia shell, 21 in. (0.53 m) deep that houses a modified Apollo-type probe, actuator-damper system, and 18 mechanical latches. The shell is an aluminum skin-stringer arrangement with 36 stringers. There is an external flange on the aft end that bolts to the Tug forward interface flange. The probe is mounted in the center of a triangular frame, which in turn is supported by six actuator-damper devices supported at the inboard flange of the module aft ring. A torque motor mounted in the probe housing provides spin-up capability for the probe head. Initial spacecraft capture is with capture latches mounted in the probe head. After initial capture, the actuator-dampers are retracted and hard docking is achieved through 18 mechanical latches on the perimeter of the 10-ft (3.05-m) dia module.

All flight loads are transmitted through the latches and outer structure rather than through the docking mechanism. For a delivery and retrieval mission, the spacecraft is installed with hard latches and deployed by unlatching and extending the actuator-dampers. For the Final Option 3A vehicle, the same method is used, but the module 6 ft (1.83 m) in diameter rather than 10 ft (3.05 m).

2



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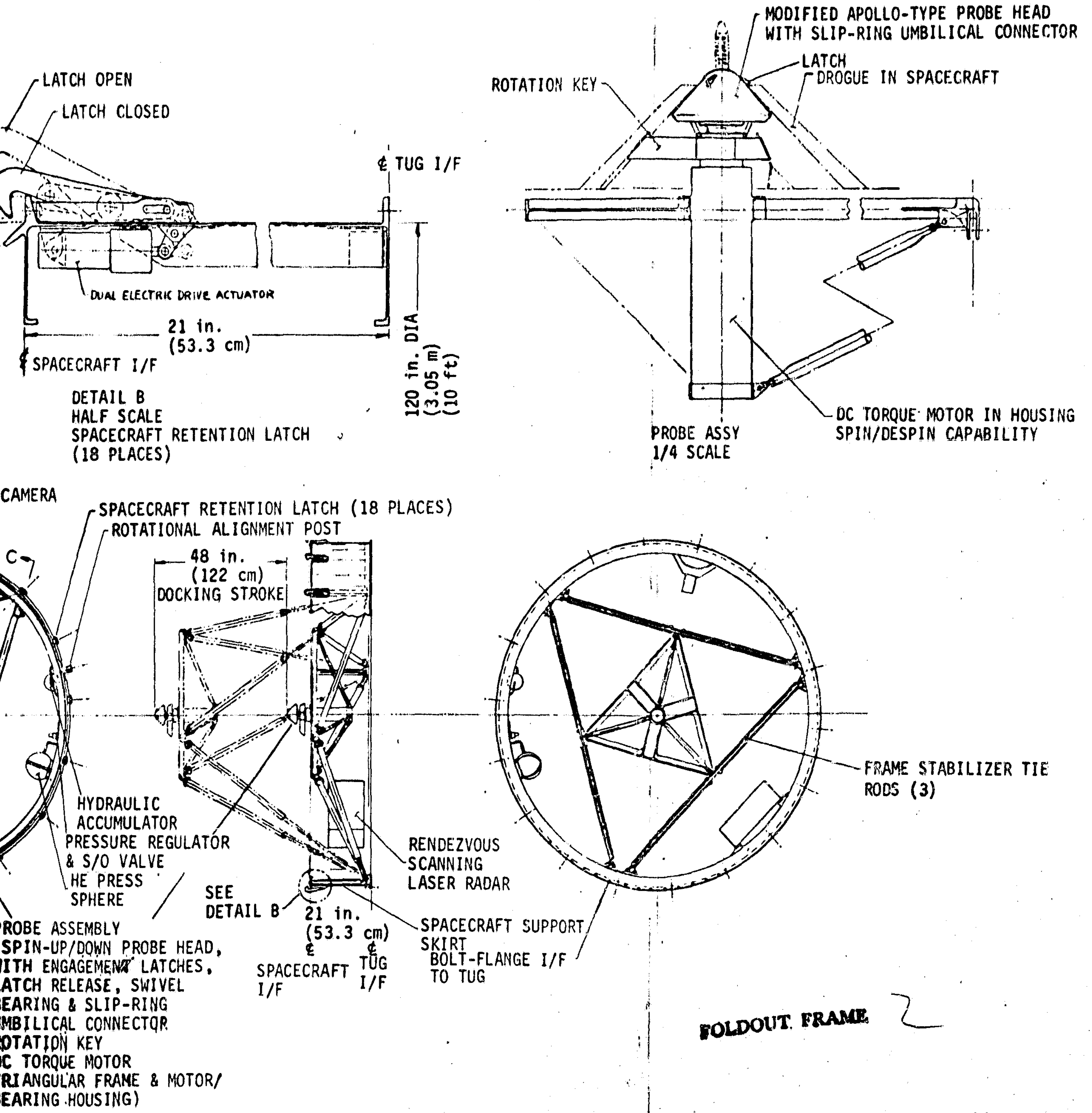

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Fig. 2.2-20 Docking Module

2.2.11 Auxiliary Stages

The auxiliary stage requirements, configurations selected, and rationale are summarized in the following paragraphs. A more detailed evaluation of the configurations is in Vol 5.0, sect. II of the *Selected Option Data Dump* (Ref 5.8).

2.2.11.1 Requirements - To improve Tug capability on some high-energy planetary missions, an auxiliary stage or kick stage is required. Requirements for the kick-stage were generally derived from Tug capability and mission model requirements. Because the study contract was to evaluate Tug designs, the kick stage was baselined as a solid to minimize cost, but a detailed trade study was not performed. It was felt that the use of a solid versus liquid kick stage should have little or no effect on Tug design and selection.

1) The kick stage requires three-axis guidance and control for proper spacecraft orbital insertion.

2) Power is required for kick-stage functions only. (Power to the spacecraft is terminated at kick-stage/Tug separation.)

3) Mission life after Tug separation is approximately 20 min, or 9½ hr from liftoff.

4) The ACPS is to provide control during solid motor burn, coast, attitude hold during spacecraft separation, and vernier capability to accommodate dispersions in solid-motor total impulse.

5) The solid-motor thrust level shall be such that the spacecraft g level shall not exceed 3.6.

6) The kick stage shall be designed to be fail safe.

2.2.11.2 Candidates Considered/Selection Methods - At the Requirements Assessment meeting (Ref 5.3), the auxiliary or kick stage was shown to significantly enhance both deep-space and geostationary capability. At that time, the kick stage was also being considered for spacecraft retrieval. The mission mode was to attach the stage to the spacecraft before delivery and to deorbit the spacecraft at some later date. The Tug would then retrieve the spacecraft from the lower-energy orbit. The auxiliary stages were designated VP-1 (Velocity Package 1), VP-2, and VP-3 (VP-1 + VP-2). Stages used existing solid propellant motors--VP-1 with 2300 lb (1043 kg) of propellant and VP-2 7300 lb (3311 kg).

After the Requirements Assessment meeting, two new requirements were imposed on the kick stage. Its thrust level was restricted to 3.6 g maximum, and attachment of deorbit kick stages for the operational life of the spacecraft was ruled out due to the possible effect on spacecraft design. Because of the g-level restriction, solid- as well as liquid-propellant kick stages were evaluated. These data were presented at the First Review presentation (Ref 5.4) in the System Panel meeting. There were again three configurations: one with 3000 lb (1361 kg) of propellant, another with 10,000 lb (4536 kg) and a combination of the two. However, data received from both Hercules and Thiokol confirmed the feasibility of slow-burning solid propellants to meet the g-level restriction. Because the type of propellant was not significant in Tug selection, solid propellants were selected due to cost and simplicity of operations.

At the Program Concept Evaluation (Ref 5.5), further refinement of the auxiliary stage requirements led to addition of a small deorbit solid stage with 1400 lb (635 kg) of propellant. The deorbit stage, designated deorbit kick motor, would be attached to the spacecraft at the time of retrieval from orbit by the Tug. The kick stage would then deorbit the spacecraft, where it would be retrieved by a later Tug flight. Closer examination of this mission mode revealed that it was more efficient and less complex to simply deorbit the spacecraft with the Tug. This mode is defined as delayed retrieval and uses the energy previously required to take the auxiliary stage to orbit for spacecraft deorbit. The new mission mode reduced both the total quantity and types of kick-stage configurations required. The limited use of the auxiliary stage to accomplish the mission model is shown in Table 1.4-4.

2.2.11.3 Configurations Selected - There are three kick stage configurations, a small 420,000 lb-s (1.87×10^6 N-s) impulse stage designated KS 1.5, a larger 2,900,000 lb-s (1.29×10^7 N-s) impulse stage designated KS 10, and a two-stage configuration consisting of KS 1.5 and KS 10. The smaller kick stage was selected at growth Burner II size in hopes of using existing hardware. For expendable Tug missions, this is the most efficient size based on mission model requirements. It also provides high ΔV for small spacecraft, while maintaining a spacecraft g level less than 3.6. The larger kick stage was selected for heavy planetary missions. Although the exact size was not critical, sizing is for a geostationary apogee kick motor based on the storable Tug capability.

The third configuration combined the large and small kick stage in a two-stage configuration to provide program flexibility while maintaining low cost by having only two basic kick stages. The two-stage kick-stage configuration provides even higher ΔV for small spacecraft, while still maintaining a g level less than 3.6.

Although the kick-stage configuration is somewhat different when used with single-stage Tugs (Final Options 1, 2, and 3) compared to the stage-and-a-half Tug (Final Option 3A), for this report, the configuration discussed is for the single-stage Tug.

The KS 1.5 kick stage (Fig. 2.2-21) is 10 ft (3.05 m) in diameter, 5 ft 5 in. (1.65 m) long and has a total weight plus 10% contingency of 2146 lb (973 kg). KS 10 (Fig. 2.2-22) is also 10 ft (3.05 m) in diameter, but 6 ft 10 in. (2.08 m) long and has a total weight plus 10% contingency of 11,680 lb (5298 kg).

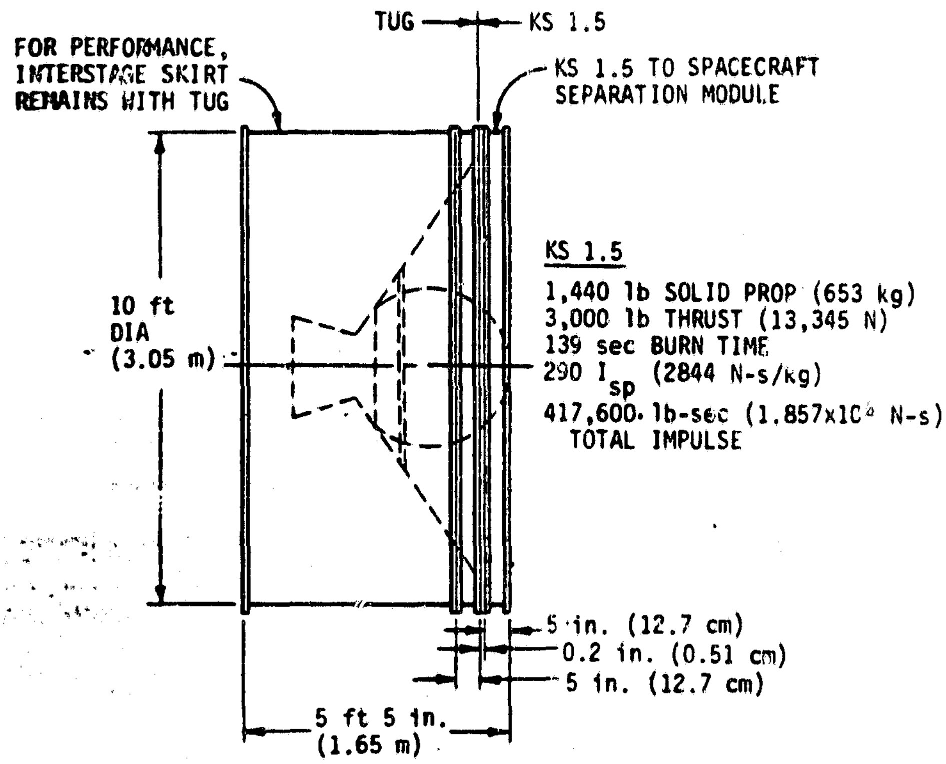


Fig. 2.2-21 Kick Stage 1.5

KS 1.5 stacked above KS 10 (Fig. 2.2-23), designated KS 10/1.5, is 11 ft 10 in. (3.61 m) long. The assembly has a total weight plus 10% contingency of 11,808 lb (5356 kg) for the lower stage and 1972 lb (894 kg) for the upper.

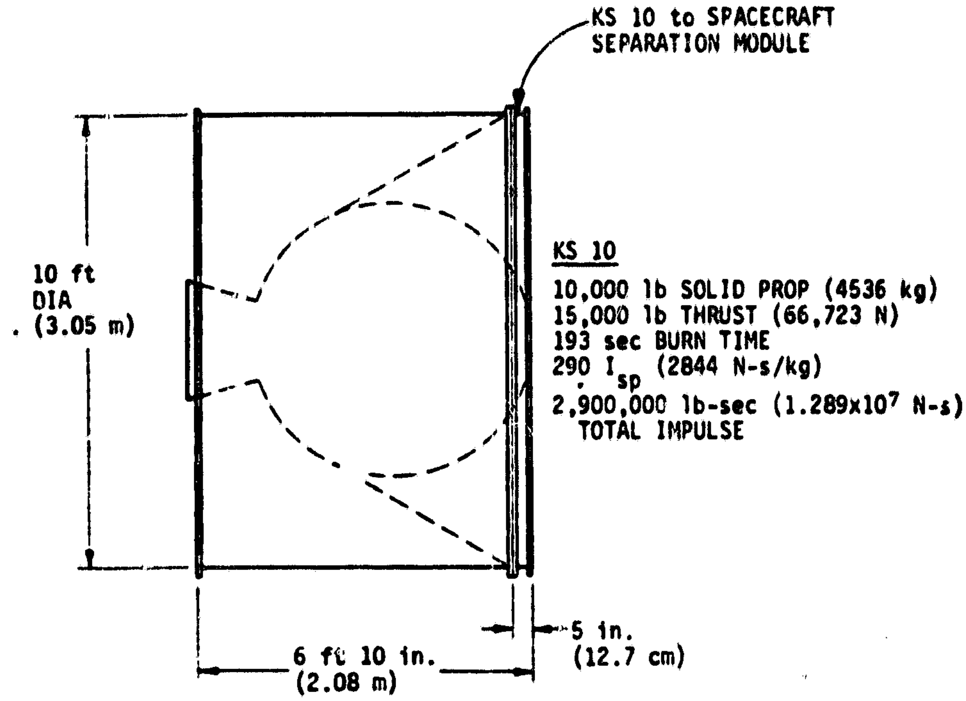
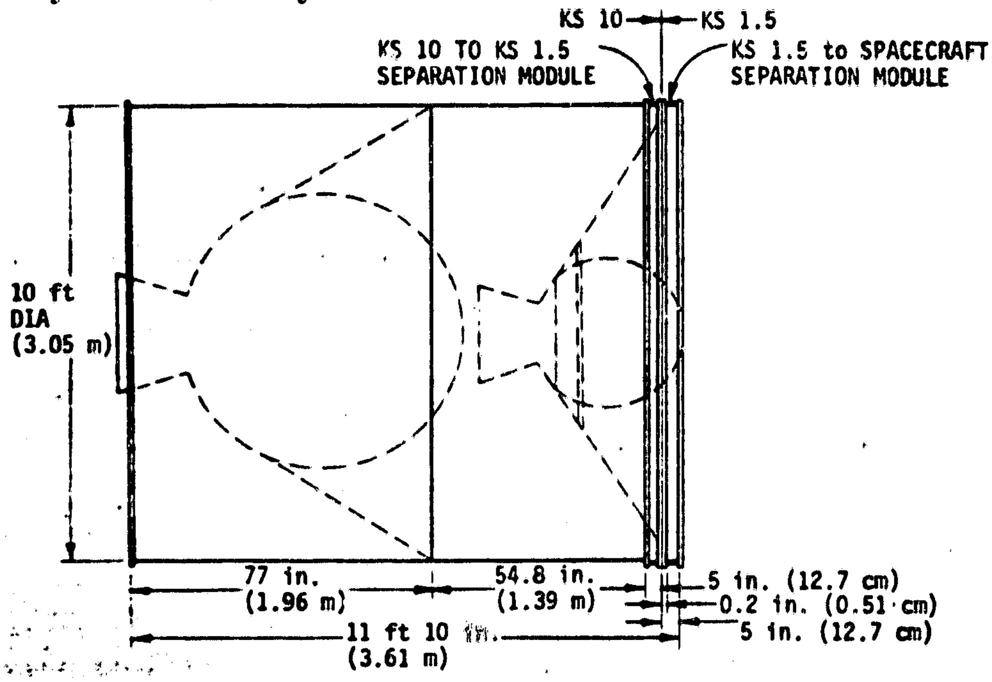


Fig. 2.2-22 Kick Stage KS 10



KS 10	KS 1.5
10,000 lb SOLID PROP (4536 kg)	1,440 lb SOLID PROP (653 kg)
15,000 lb THRUST (66,723 N)	3,000 lb THRUST (13,345 N)
193 sec BURN TIME	139 sec BURN TIME
290 I_{sp} (2844 N-s/kg)	290 I_{sp} (2844 N-s/kg)
2,900,000 lb-sec (1.289×10^7 N-s) TOTAL IMPULSE	417,600 lb-sec (1.857×10^6 N-s) TOTAL IMPULSE

Fig. 2.2-23 Kick Stage KS 10/1.5

The use of kick-stage arrangements as applied to the final options is as follows:

Final Option 1 - KS 10, 1.5, 10/1.5

Final Option 2 - KS 10

Final Option 3 - KS 10, 10/1.5

Final Option 3A - KS 10, 10/1.5

2.2.11.3.1 Solid Rocket Motor - Motors for KS 10 and KS 1.5 have spherical lightweight cases (Ti-6Aℓ-4V or glass fiber) with partially submerged exhaust nozzles with an expansion ratio of approximately 50:1, permitting a short, compact stage. Two igniters, installed at the rear of the motor case, are provided for the KS 10 motor. The KS 1.5 motor has one igniter mounted at the front of the case. The motor cases are loaded with slow-burning propellants (Class 2), which limits the stage acceleration to 3.6 g for the required total impulse.

Based on preliminary information from various solid rocket motor manufacturers, the following data were used for kick stage design:

Parameter	KS 10	KS 1.5
Total impulse required, lb-s (N-s)	2,900,000 (1.289×10^7)	420,000 (1.868×10^6)
Propellant weight, W_{PR}, lb (kg)	10,000 (4,536)	1,440 (653)
Thrust, lb (N)	15,000 (66,723)	3,000 (13,345)
Specific impulse, s (N-s/kg)	290 (2,844)	290 (2,844)
Burning time, s	193	139
Empty motor weight, W_e, lb (kg)	900 (408.2)	146 (66.2)
$\lambda = \dfrac{W_{PR}}{W_{PR} + W_e}$	0.91	0.908
Motor diameter, in. (m)	72 (1.83)	37 (0.94)
Motor length, in. (m)	86 w/igniter (2.18)	56 (1.42) 50 (1.27) w/o igniter

2.2.11.3.2 Structure - Each kick-stage structure consists of the motor thrust structure, skirt, equipment support struts and brackets, and the spacecraft interface.

The thrust structure is an aluminum skin-stringer conic structure that supports the rocket motor, extending radially to the skirt structure for uniform load distribution.

Each skirt is aluminum skin-stringer construction, 10 ft (3.05 m) in diameter. The KS 10 skirt is 6 ft 5 in. (1.96 m) long, while the KS 1.5 skirt is 5 ft (1.52 m) long. The KS 1.5 skirt is not used to support equipment, permitting retention of the skirt at staging either with the Tug or with KS 10, depending on the mission configuration.

The spacecraft interface is a 10-ft (3.05-m) dia by 5-in. (12.7-cm) deep aluminum separation module containing the separation ordnance and spacecraft deployment assembly.

Thermal protection is provided by thermal paint and selected applications of multilayer insulation.

2.2.11.3.3 Avionics - The avionics are the same for each kick stage. For the dual kick-stage configuration, the power, load distribution, and guidance, navigation, and control (GN&C) functions are in the forward kick stage (KS 1.5) only.

The GN&C subsystem contains three gyros, three accelerometers, and associated integrated circuits. The steering logic indicated is not in final form; however, it does show that the pitch and yaw profile will be related to the performance and thrust misalignment of the kick stage and not just a function of time. This is an improvement over the Burner II logic and permits achievement of the 3-σ state vector planetary-insertion requirements as now understood.

The ACPS subsystem will be operational through a phase-plane autopilot in both powered and coast flight due to the fixed main motor. The kick-stage GN&C box will have all the sensing capability of a strapdown IMU, but without the ability to relate its data, sensed in body coordinates to an inertial frame; i.e., it does not contain the electronic gimbal algorithm, nor are its sensors aligned well enough to take advantage of this mathematical routine should the integrated circuits be built into it.

The electrical power and distribution subsystem consists of two main batteries, an auxiliary battery and power distributors, and required wiring and connectors. The main batteries supply required power to propulsion and avionics subsystems and the spacecraft. The auxiliary battery is used primarily for ordnance requirements.

This system also contains the ordnance and ordnance circuitry for spacecraft separation and for the SRM igniters. Each SRM igniter unit is provided with an electromechanical safe and arm device as well as redundant squibs that initiate motor ignition. In addition, each ordnance circuit has its own safe and arm device to prevent accidental squib ignition.

The spacecraft communications subsystem will be modified to permit transmission of kick-stage data by the spacecraft transmitter before separation, eliminating the need for a separate communications subsystem on board the kick stage. This will include a 5-lb (2.27-kg) weight addition to the spacecraft.

2.2.11.3.4 <u>Attitude Control</u> - The ACPS for each kick stage uses monopropellant N_2H_4 with gaseous nitrogen at 3400 psi (2344 N/cm^2) as the pressurant. All system components were selected from flight-qualified hardware and both kick stages use the same components.

The ACPS for the two kick stages uses a pressure-regulated pressurization system with 12 thrusters. In pitch and yaw, there are eight thrusters, each with a maximum thrust of 27 lb (120.1 N). In roll, there are four thrusters, each with a maximum thrust of 5 5.3 lb (23.6 N). The thrusters have series valves and are arranged in pairs to provide redundancy in each axis.

The total ACPS propellant load, including reserves and contingency, is 60 lb (27.2 kg) and 120 lb (54.4 kg) for the KS 1.5 and KS 10, respectively.

2.2.12 Cradle

2.2.12.1 Requirements - The cradle must provide dump provisions for the Tug main propellants, both fuel and oxidizer, as well as structural and electrical interfaces with both the Tug and Orbiter. In accomplishing this, the cradle must provide:

1) Structural support of the Tug and its spacecraft during orbiter operation with a four-point statically determinant cradle-to-Orbiter load system;

2) A Tug-to-cradle structural restraint system that need not be statically determinant, but with capability for remote latching and unlatching;

3) A remotely actuated quick disconnect with remote reconnect capability for the Tug-to-cradle propellant dump lines and electrical umbilical;

4) Support for cradle-to-Orbiter umbilical sections for both propellant dump lines and electrical connectors.

2.2.12.2 Final Option Definition

a. *Cradle for Final Options 1, 2, and 3* - Figure 2.2-24 shows the cradle design used for single-stage options. Cradle length is 15 ft 4 in. (4.67 m) and the outside diameter is nearly 15 ft (4.57 m). A clam-shell door provides means to pick up the Tug over its full circumference rather than only the lower half. Cradle-to-Orbiter interface points are statically determinant as defined in *Payload Accommodations* (Ref 5.13) with two vertical and two longitudinal reactions taken at Orbiter sta 1041, one vertical at Orbiter Sta 1134.5, and one lateral at Orbiter Sta 1040. The Tug-to-cradle structural tie is statically indeterminant with eight lateral (Y), eight vertical (Z) ties, and a vee-groove clamp for longitudinal (X) loads.

b. *Final Option 3A Cradle* - Figure 2.2-25 shows the cradle design used for the stage-and-a-half vehicle. The length is 20 ft 10 in. (6.35 m) and the diameter is nearly 15 ft (4.57 m). The cradle is made up of two deep multicell box beams running full length along each side, tied together at each end by bulkhead-type frames. The forward frame has a fixed lower portion machined from 7075-T73 aluminum forgings and an upper clamshell portion actuated by powered hinges and with an upper centerline tension tie that is mechanically actuated. The aft bulkhead covers only the lower portion, and it also is machined from 7075-T73 aluminum forgings. The box beams are made of 7075-T6 aluminum skins over 7075-T73 aluminum machined ribs with 7075-T73 aluminum extruded-angle longitudinal stiffeners along the full length of the beams.

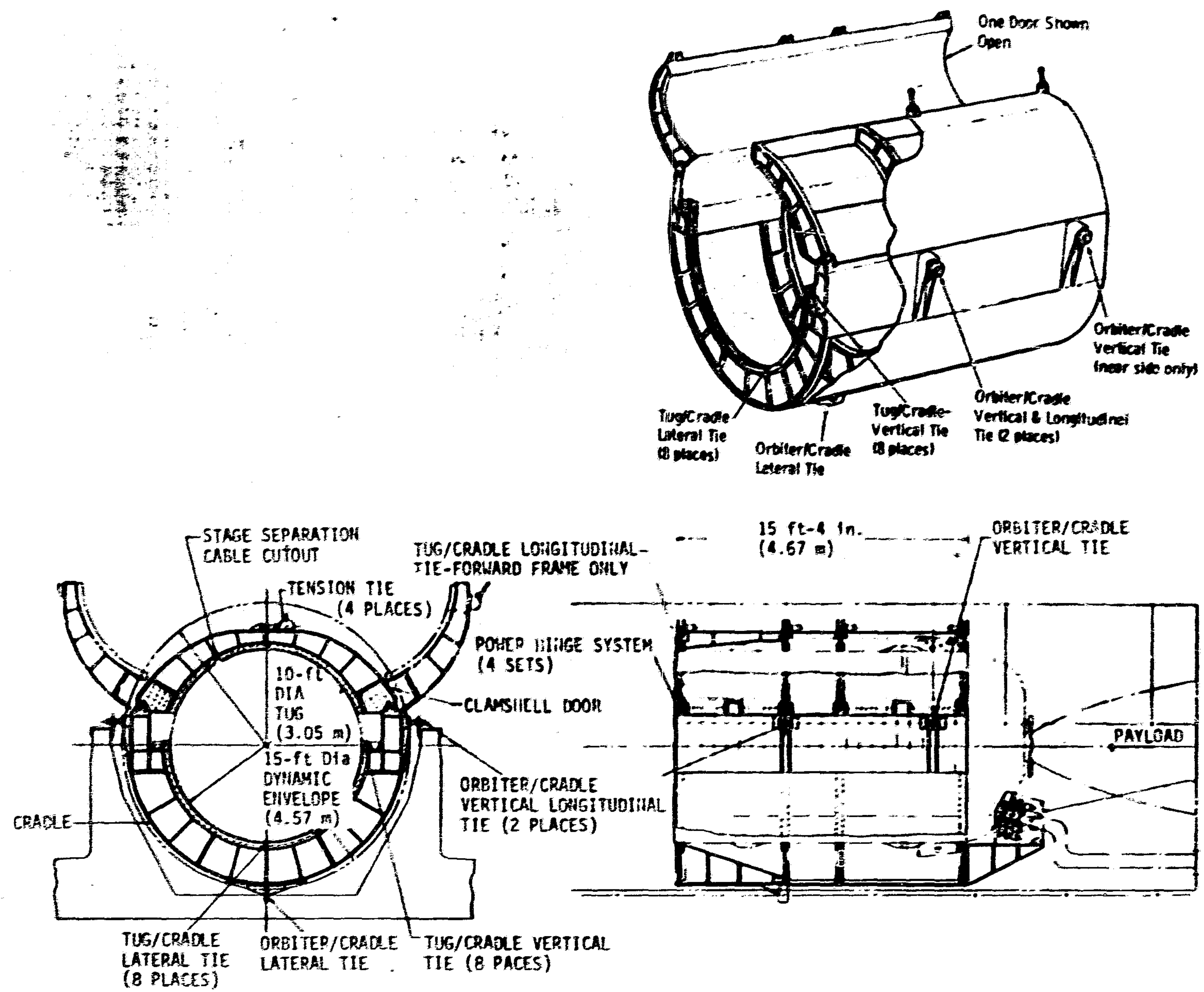


Fig. 2.2-24 Cradle Concept for Final Options 1, 2, and 3

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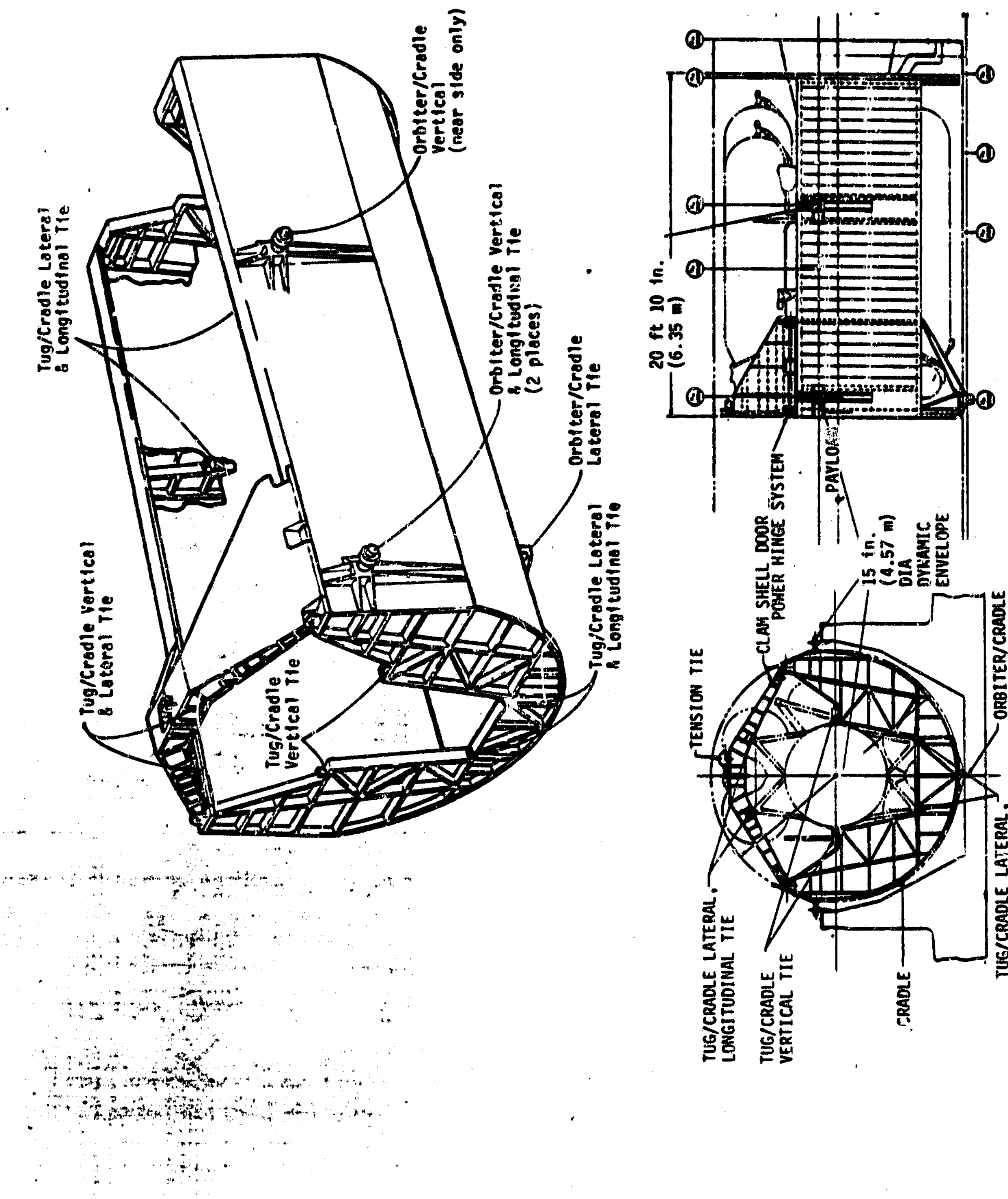

Fig. 2.2-25 Cradle Concept for Final Option 3A

Figure 2.2-26 shows the Tug-to-cradle umbilical plate concept.

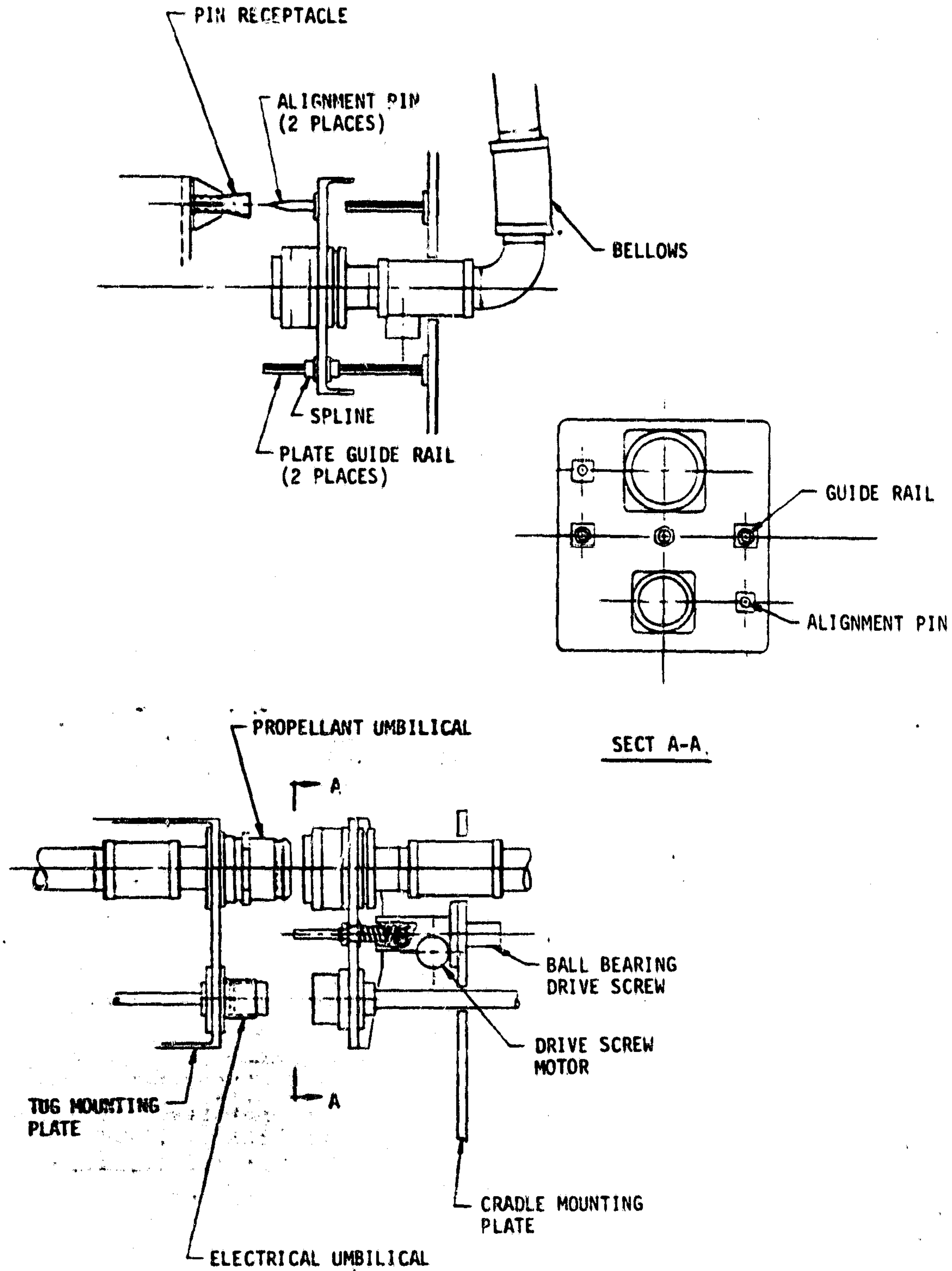

Fig. 2.2-26 Tug/Cradle Umbilical Separation-Plate Concept

3 CONFIGURATION CONCEPTS

This section generally defines the activity taking place in Task 3. Mission requirements were defined in Task 1. Data on all potential subsystems were collected and evaluated in Task 2, with each subsystem subjected to a course screening based on the requirements as known at that time. The selected subsystem candidates surviving the Task 2 screening were eligible for consideration in the overall Tug configuration synthesis process in Task 3. The following paragraphs provide an overview of the Tug configuration conceptual design activity, including synthesis methods, concepts considered, methods for evaluation and selection, and finally, the Tug configurations selected for further detailed definition in Task 5.

2.3.1 Configuration Synthesis Methods

As applied to this study, configuration synthesis is defined as the process of developing the conceptual Tug configurations for each of seven capability options that will satisfy the "bucket" requirements and those mission/design requirements defined in paragraphs 2.1 and 2.2. It should be noted that the term "capability option" as defined in Task 3 is not the same as the term "final option" as used in Task 5. The options were redefined by NASA/DOD after the Program Concept Evaluation presentation (Ref 5.5), and are referred to as final options in Task 5. Each of the seven capability options as used in Task 3 are defined below.

2.3.1.1 Tug Concept Selection Capability Options (Buckets) - The seven NASA/DOD provided Tug capability options for use by all Tug system study contractors for the concept selection milestone are defined as follows:

a. *Option 1: Interim Tug (without Rendesvous and Docking), Direct-Developed* - This direct-developed limited-capability Tug will have its IOC on December 31, 1979. The vehicle must deploy 3500 lb (1588 kg) in geosynchronous orbit. It will not have retrieval capability. It will use subsystems that have early availability. The degree of autonomy is unspecified and is to be the subject of trade studies. Because this option is not to be phased, evolutionary capability shall not be considered in the design.

b. *Option 2: Interim Tug (with Rendezvous and Docking), Direct-Developed* - This direct-developed medium-capability Tug will have its IOC on December 31, 1979. A higher-performance propulsion system is expected than that in Option 1. Option 2 will have geosynchronous retrieval capability. The degree of autonomy is a tradable item. Minimum performance will be 3500 lb (1588 kg)

in a geosynchronous deployment mode and 2200 lb (998 kg) in a geosynchronous retrieval mode. Because Option 2 is not to be phased, evolutionary capability shall not be considered in the design.

c. Option 3: Interim Tug (without Rendezvous and Docking), Phased to Interim Tug (with Rendezvous and Docking) - This phase-developed Tug will have performance and IOC requirements consistent with the definitions of Options 1 and 2. Evolutionary capability shall be considered in the design of Option 1 in this case. Costs and schedules for direct-developing the identical Option 2 obtained from this phased program (with an IOC of December 21, 1983) shall be provided. Design penalties due to phasing will be minimized.

d. Option 4: Full-Capability Tug, Direct-Developed - This direct-developed full-capability Tug will have its IOC on December 31, 1983. Sensitivity of factors relevant to moving the IOC up two years will be performed. The actual date should be based on the optimum development cost. It will have retrieval and servicing capabilities. The latter is not to be used as a driver, however. All requirements for this option shown in the government data package will be applied. Minimum performance will be 3500 lb (1588 kg) in a geosynchronous retrieval mode. Medium to high autonomy is desired.

e. Option 5: Interim Tug (without Rendezvous and Docking), Phased to Full-Capability Tug - This phase-developed Tug will have performance and IOC requirements consistent with the definitions of Options 1 and 4. Design penalties due to phasing will be minimized.

f. Option 6: Interim Tug (with Rendezvous and Docking), Phased to Full Capability Tug - This phase-developed Tug will have performance and IOC requirements consistent with the definitions of Options 2 and 4. Design penalties due to phasing will be minimized.

g. Option 7: Interim Tug (with Rendezvous and Docking), Directly Developed - This direct-developed Tug will have its IOC on December 31, 1983. The performance requirements are consistent with the definition of Option 2.

2.3.1.2 <u>System/Subsystem Synthesizing Procedure</u> - The innumerable technical, safety, and economic variables for the study determined the detail depth and number of iterations required for defining the conceptual Tug systems to the design, manufacturing, and operational levels. The general steps performed in the process are listed below, with their interrelationship shown in Fig. 2.3-1.

Step 1: Determine Tug general performance requirements to establish sizing. This was accomplished in Task 1.

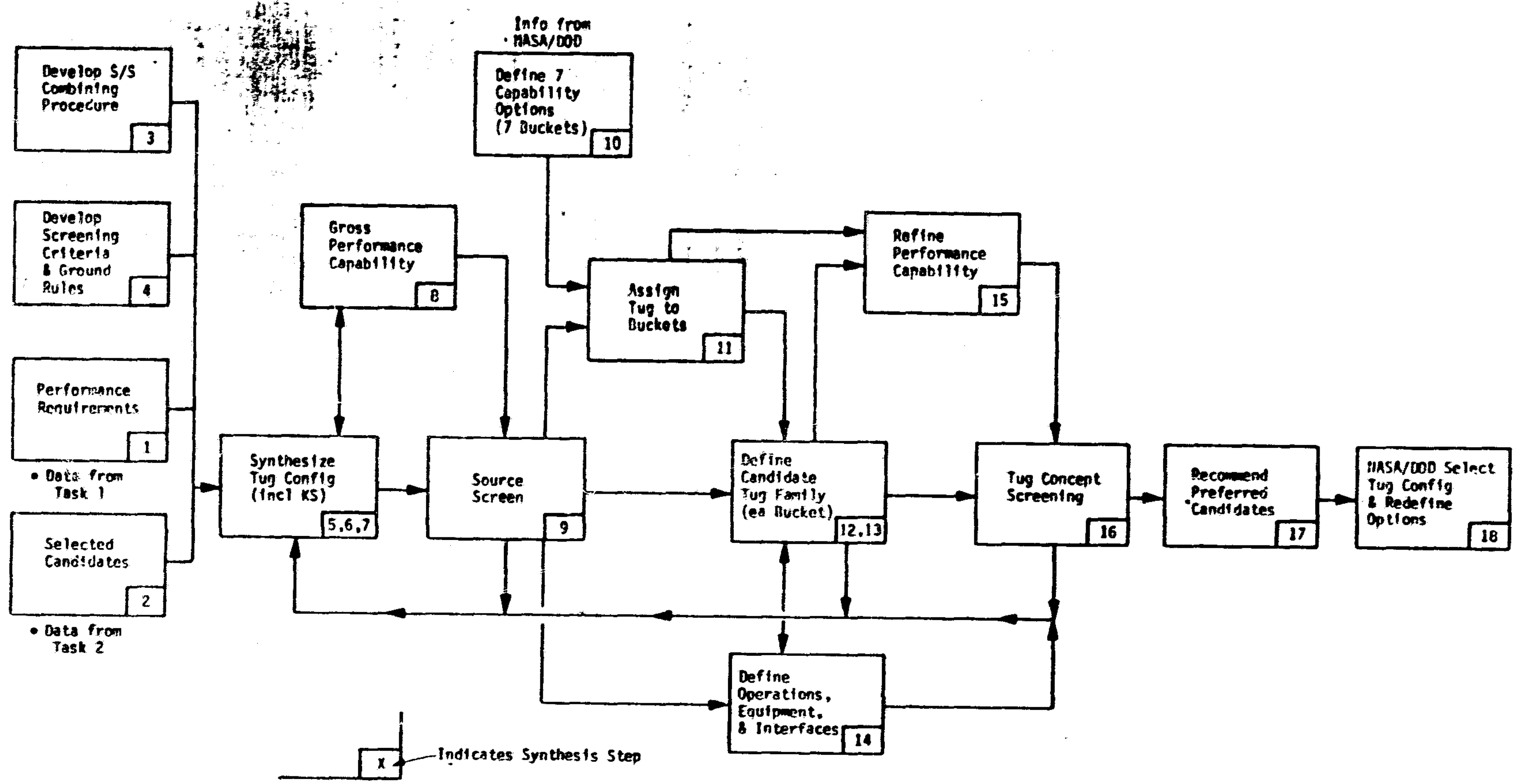

Fig. 2.3-1 Configuration Synthesis Interrelationships

Step 2: Determine selected subsystem candidates. This was accomplished in Task 2.

Step 3: Develop subsystem combining procedure.

Step 4: Develop screening criteria and ground rules.

Step 5: Select basic vehicle configurations (single-stage or multistage) that could be used to satisfy the mission requirements.

Step 6: Lay out feasible structural arrangements for the basic vehicle configuration and determine basic weights.

Step 7: Initially screen structural concepts based primarily on weight, with additional considerations of cost, manufacturing techniques, safety, reliability and maintainability (reuse/refurbish), and given ground rules.

Step 8: Determine gross performance capability of each surviving configuration using calculated structural weights and assumed weights of other subsystems (minimum). Performance capability is based on parametric methods for delivery only, retrieval only, and round trip, expressed as weight of Tug payload (spacecraft).

Step 9: Conduct first screening iteration based on performance.

Step 10: Receive capability option definitions from NASA/DOD.

Step 11: Assign Tug configurations to match desired capability options. Assure imperative criteria are met.

Step 12: Define candidate Tug families consisting of the single or multiple Tugs with their corresponding operations, equipment, and interfaces required to satisfy the seven capability option requirements.

Step 13: Select specific subsystems to match Tug configurations and mission requirements.

Step 14: Define operations, equipment, and interfaces for typical Tug configurations.

Step 15: Refine performance capability of each configuration using calculated weights for structure and all other subsystems and for each engine option.

Step 16: Perform second screening iteration.

Step 17: Martin Marietta select recommended Tug family for each capability option.

Step 18: NASA/DOD select Tug configurations and define final options for Task 5 study.

2.3.1.3 Synthesis Ground Rules - Definition of the capability options permitted certain basic rules other than those of the basic *Data Package* (Ref 5.12) to be formulated and applied in the Tug configuration synthesis process and are:

- For delivery-only missions, remove rendezvous and docking hardware from Tug to enhance spacecraft delivery capability and to preclude unnecessary aging of rendezvous and docking hardware.

- Do not change tank or structure materials in phase development.

- Phase develop in one step from 1979 to 1983.

- Do not change tank configuration in phase development (maintain same mixture ratio).

- Use as phase development drivers:

  Engine (OME or Bell to high P_c)

  Rendezvous and docking to accommodate retrieval

  State-of-the-art avionics to "lighter" avionics.

2.3.2 Tug Concepts Considered

The following paragraphs present the basic structural Tug concepts considered, selected subsystem candidates for use in configuration synthesis, and the candidate Tug configurations used for evaluation in each capability option (bucket).

2.3.2.1 Basic Structural Concepts - Table 2.3-1 shows the selected structural subsystem candidates surviving the Task 2 screening process.

Table 2.3-1 Selected Structural Subsystem Candidates

Structural Subsystem Designator	Description
Selected Candidates	Single stage, 57,000 lb (25,855 kg) propellant; mixture ratio, 2:1
IA1	Isolated tanks, Titan III Stage II tank arrangement
IA2	Isolated tanks, fuel tank forward, elliptical domes
IA3	Isolated tanks, equal-volume tanks, (mixture ratio, 1.65:1)
ID	Common-dome tanks, hemispherical domes
Selected Candidate	Two-stage, 28,500 lb (12,927 kg) propellant per stage; mixture ratio, 2:1
IIIC	Common-dome tanks, elliptical domes
Selected Candidate	Stage-and-a-half, 57,000 lb (25,855 kg) propellant; tank arrangement, core and drop tanks; mixture ratio, 2:1
IVE	20/80 propellant split, core plus two drop tanks, common elliptical domes

2.3.2.2 Subsystem Candidates - Table 2.3-2 shows the selected subsystem candidates from the subsystem evaluation tasks discussed in paragraph 2.2, with their designators used for identification and tracking of the various Tug configurations.

2.3.2.3 Kick-Stage Concepts - Figure 2.3-2 shows the basic kick-stage concepts used in this phase of the study. These were later redesigned in the program definition task. (para 2.2.9.)

Table 2.3-2 Selected Subsystem Candidates Summary

Subsystem	Designator	Description
Materials	LT Al	Aluminum, light weight, minimum tank wall 0.020 in. (0.508-mm) one-piece domes
	Hvy Al	Aluminum, heavy weight, minimum tank wall 0.035 in. (0.889-mm) welded gore section domes
	Ti & C	Titanium plus composites, minimum tank wall 0.012 in. (0.305-mm)
Tank Arrangements	None	Isolated tanks, Titan III, Stage II tooling & configuration
		Isolated tanks, new design
		Common dome (spherical & elliptical)
Propellant	None	N_2O_4/MMH
Engines	E-325-B	Bell 8096B, I_{sp} = 325 sec nom (3187 N-s/kg), F = 16,000 lb (71,172 N), MR = 1.78
	E-325-0	OME existing, I_{sp} = 325 sec nom (3187 N-s/kg), F = 7500 lb (33,362 N), MR = 2.0
	E-325	OME uprated, I_{sp} = 325 sec nom (3187 N-s/kg), F = 12,000 lb (53,379 N), MR = 2.0
	E-338	New Class I, I_{sp} = 338 sec nom (3315 N-s/kg), F = 12,000 lb (53,379 N), MR = 2.0
	E-344	New Class II, I_{sp} = 344 sec nom (3373 N-s/kg), F = 12,000 lb (53,379 N), MR = 2.0
Pressurization	PR-1(X)	Regulated helium - ambient storage
	PR-2(X)	
	PR-6(X)	Gas-generator cascade
ACPS	ACPS-2(8)	Monopropellant hydrazine (16 thrusters)
Thermal	TH-1	Single-stage, passive, MLI
	TH-2	Stage-and-a-half, passive, MLI
	TH-3	Single-stage, active, MLI with heat exchanger
	TH-4	Two-stage, passive, MLI
	TH-5	Single-stage, passive, thermal paint with limited MLI
Data Management		Flexible signal interface (FSI)
Communications		S-band
Power		Solar array/Ag-Zn battery
		Fuel cell
		Batteries
Rendezvous & Docking		RF radar
		Laser radar
Guidance & Navigation		Redundant strapdown IMUs with star tracker (Horizon sensor for Autonomy Level I)
		Lighweight redundant strapdown IMUs with star tracker (Horizon sensor for Autonomy Level I)
Controls		Integrated hydraulic actuators (main engine gimbal), 16-thruster ACPS (attitude control)
Autonomy Level		Level II

Avionics subsystems above were combined into the following "kits":

AV-1	1979 Type Avionics (heavy), delivery-only capability, solar-panel power, Autonomy Level II
AV-4	Same as AV-1 plus rendezvous & docking capability
AV-3	1983 Type Avionics (light), delivery-only capability, solar-panel power, Autonomy Level II
AV-2	Same as AV-3 plus rendezvous & docking capability
AV-8	Same as AV-3 except fuel-cell power
AV-7	Same as AV-2 except fuel-cell power
AV-9	Same as AV-1 except battery power only

Note: Kit concept is used for all configurations; for delivery missions, the docking Module is replaced by the separation module (see 2.2.10 & 2.2.9, respectively.)

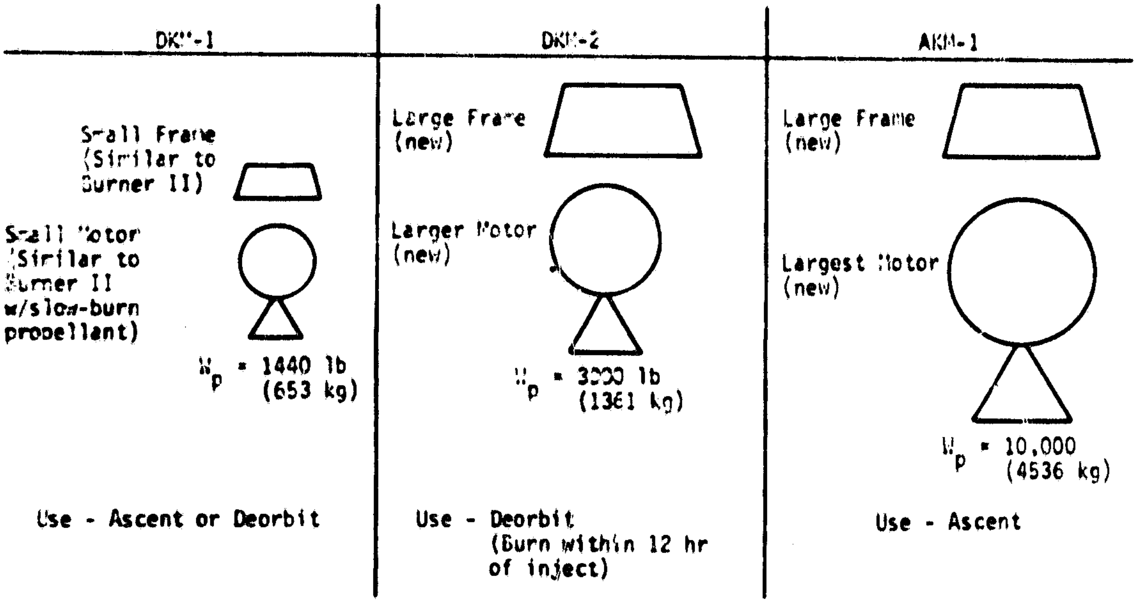

Fig. 2.3-2 Kick-Stage Concepts

2.3.2.4 Candidate Tug Configurations for Evaluation - Using the structural/subsystem concepts described above, the synthesis/subsystem combining task resulted in the generation of 48 individual Tug configurations. The screening process reduced these to 33, as shown in Table 2.3-3, that were actually qualified as candidates for further evaluation within the seven NASA/DOD-provided capability options. The 33 candidates, when combined within the options, formed 39 different candidate "families."

Table 2.3-3 Candidate Tug Systems

Stage	Designator Code	Number of Stages Synthesized
Single		(28)
	IA1	6
	IA2	11
	IA3	1
	ID	10
Dual		(12)
	IIIC	8
	IIIF	4
One-and-a-half		(8)
	IVE	8
Total Tug configuration synthesized		48
Tug configurations rejected		15
Tug configurations used		33

Table 2.3-4 is an example of the grouping of candidate Tugs within each capability option; in this case Capability Option 7. A complete list of all candidate Tugs in each of the capability options may be found in *Data Package Space Tug Systems Study (Storable)* (Ref 5.7).

2.3.3 Methods for Tug Concept Assessment and Selection

The following paragraphs describe the methods used for assessment of all Tug candidates and for selection of preferred candidates within each capability option.

2.3.3.1 Commonality Grouping and Sensitivity Values - Following the synthesis process and before actual assessment of the candidate Tug configurations, it was necessary to develop a logic for placement of each candidate in the capability option for which it was best qualified. In addition to the basic performance requirement for each option, developed logic used commonality grouping of basic configurations, with additional back-checks on specific cost sensitivities of interest.

Commonality groups were formed for each option using a single-stage, dual-stage, and stage-and-a-half Tug; each with common or comparable subsystems; i.e., common engines like OME uprated, common structure like titanium and composites, and common avionics like early 1979 state-of-the-art equipment.

Additional Tug candidates were added to each option to provide cost sensitivity. Included were such items as isolated tank arrangement versus common bulkhead, solar-panel versus fuel-cell power, passive versus active thermal control systems, phasing new Class I to Class II engines, titanium versus aluminum tanks, welded domes to one-piece domes, solar-panel versus all-battery power, and the like.

In addition, option requirements permitted placement logic to check such items as the cost of retrieval capability to the program.

2.3.3.2 Imperatives Criteria - All Tug concepts were required to satisfy certain screening requirements, including safety, reliability, compatibility with Shuttle and crew, and minimum performance (by capability option), before warranting further consideration. Some configurations were eliminated for failure to achieve the 3500-lb (1588-kg) delivery-only capability gate. Adjustments were made in component redundancy in the avionics subsystems to pass the overall vehicle reliability gate. Safety and compatibility with Shuttle/crew-imperative criteria were based on system and subsystem design experience.

Table 2.3-4. Capability Option 7 Candidate Tugs

Requirements: 1983 IOC, 3500-lb (1588-kg) delivery/2200-lb (998-kg) retrieval

Mission Model: 262 deliveries, 204 retrievals, LCR spacecraft

Candidates	Stages	Material	Avionics	Engine	Feed & Press.	ACPS	Thermal Control	Dry Wt lb	Dry Wt (kg)
IA2-3	1	Ti & C	AV-2	E-338	PR-1(2)	ACPS-2(8)	TH-1	2395	1086
IA2-4	1	Ti & C	AV-3	E-338	PR-1(2)	ACPS-2(8)	TH-1	2182	990
IIIC-5	2	Ti & C	AV-2	E-338	PR-1(4)	ACPS-2(8)	TH-4	2201 / 2287	998 / 1037
IIIC-6	2	Ti & C	AV-3	E-338	PR-1(4)	ACPS-2(8)	TH-4	1989 / 2129	902 / 966
IVE-5	1-1/2	Ti & C	AV-2	E-338	PR-1(5)	ACPS-2(8)	TH-2	3655	1658
IVE-6	1-1/2	Ti & C	AV-3	E-338	PR-1(5)	ACPS-2(8)	TH-2	3443	1561
ID-1	1	Ti & C	AV-7	E-338	PR-6(1)	ACPS-2(8)	TH-3	2401	1089
ID-2	1	Ti & C	AV-8	E-338	PR-6(1)	ACPS-2(8)	TH-3	2189	993
IA2-9	1	Ti & C	AV-2	E-344	PR-1(2)	ACPS-2(8)	TH-1	2422	1098
IA2-10	1	Ti & C	AV-3	E-344	PR-1(2)	ACPS-2(8)	TH-1	2210	1002
IA1-5	1	Hvy Al	AV-2	E-338	PR-1(2)	ACPS-2(8)	TH-1	2813	1276
IA1-6	1	Hvy Al	AV-3	E-338	PR-1(2)	ACPS-2(8)	TH-1	2600	1179
ID-3	1	Lt Al	AV-7	E-338	PR-6(1)	ACPS-2(8)	TH-3	[illegible]	1181
ID-4	1	Lt Al	AV-8	E-338	PR-6(1)	ACPS-2(8)	TH-3	2391	1084
IA1-3	1	Hvy Al	AV-4	E-338	PR-1(2)	ACPS-2(8)	TH-1	3062	1389
IA1-4	1	Hvy Al	AV-1	E-338	PR-1(2)	ACPS-2(8)	TH-1	2635	1195
IIIC-3	2	Ti & C	AV-4	E-338	PR-1(4)	ACPS-2(8)	TH-4	2450 / 2536	1111 / 1150
IIIC-4	2	Ti & C	AV-1	E-338	PR-1(4)	ACPS-2(8)	TH-4	2023 / 2164	917 / 981
IVE-7	1-1/2	Lt Al	AV-2	E-338	PR-1(5)	ACPS-2(8)	TH-2	3659	1659
IVE-8	1-1/2	Lt Al	AV-3	E-338	PR-1(5)	ACPS-2(8)	TH-2	3446	1563

2.3.3.3 Assessment and Screening Criteria - Assessment and selection criteria used in considering the merits of each Tug concept within each capability option were grouped as quantifiable criteria (cost, spacecraft performance, mission capture) and unquantifiable criteria (other performance capabilities, operational complexity, risk, spacecraft effects, evolutionary and growth capability). Both quantifiable and nonquantifiable criteria were derived from general criteria provided by NASA and DOD.

a. *Quantifiable Criteria* - Assessment of Tug concepts with regard to quantifiable criteria was an application of key discriminators against the criteria shown in Table 2.3-5. The mission capture analysis was performed using the flight techniques developed for the applicable Tug configurations; i.e., single, dual or stage-and-a-half with/without kick stages (para 2.1 and 2.2)

Table 2.3-5 Quantifiable Assessment and Selection Criteria

Cost	
Criteria	**Discriminators**
DDT&E	Flight Operations Analysis
Investment (Production)	Ground Operations Analysis
Operations	IOC
Cost/Flight	Program Schedule
Total Program Cost	
Total Tug Cost	
Mission Capture	
Criteria	**Discriminators**
Performance Capability	Spacecraft Weight
Delivery	Flight Techniques
Retriveal	Spacecraft Types
Round Trip	Traffic Model
Number of Shuttle Flights	100% Capture
Geostationary	Spacecraft Grouping
Midinclination	Diameter
Polar	Length
Planetary	Weight
Spacecraft Requiring Two Flights	Tug Length
Kick Stages Required	
Total Shuttle Flights for 100% Capture	

2. *Unquantifiable Criteria* - Valid assessment of Tug concepts also required detailed inspection of system and subsystem elements based on unquantifiable criteria in Fig. 2.3-3 to establish the real worth of each candidate Tug configuration.

Each element within a subsystem was examined for merit against unquantifiable criteria. The actual analysis was performed in three steps. The first was at the level of detail necessary to identify which of the subsystem/system elements was affected by each particular item of the unquantifiable criteria. The frequency a given subsystem served as a discriminator is indicated in Fig. 2.3-3.

The second step was a detailed analysis of each candidate with regard to areas identified by the discriminators. The results of this analysis were compared to other candidates within each subsystem for each Tug configuration, a rating from 1 to 10 was assigned and entered in a subsystem trade study matrix as shown in Fig. 2.3-4, as selection data. An example of the logic used in establishing the 1 to 10 rating for each subsystem is shown in Table 2.3-6.

As a final step before selection, each Tug concept was evaluated for worth by relative weighting of the subsystem data in the Subsystem Trade Study Matrix and displayed in the format shown in Fig. 2.3-5. The resulting scores, expressed relative to each other, were expressed as "technical factors" ratings.

2.3.3.4 <u>Trade Studies</u> - In addition to evaluating Tug candidates against assessment and selection criteria, certain specific technical trade-offs were performed to confirm assessment results. Some of the more significant results are shown below.

a. Basic Vehicle Configuration Comparison - The results of this trade study indicated a preference for single-stage Tugs over multiple-stage. Table 2.3-7 compares the advantages and disadvantages.

b. Titanium versus Aluminum Tanks - It was determined that titanium tank material was preferred over aluminum because of:

- High fracture toughness in welded areas (longer life, safer);
- Higher material toughness (more resistance to handling damage);
- Easier welding in thin gages;
- Minimum gages for Tug comparable to minimum gages used on Titan.

Criteria	Discriminators						
	Matl	Avionics	Engines	Press/ Feed/ Dump	ACPS	Thermal Control	Struct Types
Performance Capability							
Abort				X	Same subsystem used on all configurations		X
Reuse		X		X		X	X
On-Orbit Life		X		X			
Guidance Accuracy		X					
Operational Complexity							
Shuttle Interface		X		X			X
Flight Staging		X		X			X
Autonomy (Flight)		X					
Autonomy (Development)		X					
Ground Maintenance		X	X	X		X	X
Ground Handling		X		X			X
Support Equip Req		X		X			X
Risk							
Schedule	X	X	X	X			X
Cost	X	X	X	X			X
Performance & Capability	X	X	X	X			X
Spacecraft Effects							
Tug Length							X
Spacecraft Design Change		X					
Evolution & Growth Capability							
Potential Growth		X	X				

Figure 2.3-3 Unquantifiable Assessment and Selection Criteria

Subsystem Description \ Selection Criteria	Reuse	On-Orbit Life	Guidance Accuracy	Orbiter Interface	Flight Staging	Autonomy (Flt)	Autonomy (Dev)	Ground Maintenance	Ground Handling	Support Equip Req	Sched Risk	Cost Risk	Perf & Cap Risk	Spacecraft Design Change	Potential Growth
Material															
Heavy Al											10	10	10		
Light Wt Al											8	10	10		
Ti & Composite											9	10	10		
Avionics															
AV-1	10	10	10	10	10	10	10	8	8	8	7	7	7	8	8
AV-4	10	10	10	10	10	10	10	8	8	8	7	7	7	8	8
AV-3	10	10	10	10	10	10	10	8	10	9	3	3	3	10	10
AV-2	10	10	10	10	10	10	10	8	10	9	3	3	3	10	10

Engines

Pressurization

ACPS

Thermal Control

Structural Concept

Rankings Based on 10 = Good
1 = Poor

Figure 2.3-4 Subsystem Trade-Study Summary Matrix

Table 2.3-6 Example of Subsystem Rating Logic

Ground Handling		
Feed, Dump, & Press. Candidates	**Matrix Value**	**Trade-Off Considerations**
PR-1(-) S/S, Reg He	10	Propellant & commodity fill operation simplest. Simplest system to install.
PR-1(4) Dual-Stage, Reg He	9	Two systems for fill operation. Requires more installation time.
PR-1(5) 1½-Stage, Reg He	8	Due to drop tanks, three systems require filling. Requires more installation time.
PR-6(1) S/S, Cascade Press., Dedicated Gas Generator	5	Cryogenics handling, overall complxity, lengthened installation time, additional commodity (LH_2) requires added interface & new safety hazard.

Capability Option 3 Candidate Selection										
Selection Criteria		Relative Weighting Factor	Candidate Concepts							
			IA2-B, 7		IIIC-2, 1		IVE-2, 1		IA2-B, 4, 3	
			Score	Merit	Score	Merit	Score	Merit	Score	Merit
Performance & Capability										
Abort		4	10	40	7	28	3	12	10	40
Reliability (Interim Stg)										
Number of Reuses		5	10	50	10	50	5	25	10	50
On-Orbit Life		5	10	50	10	50	10	50	10	50
Guidance Accuracy		5	10	50	10	50	10	50	10	50
Operational Complexity										
Orbiter Interface		5	10	50	8	40	6	30	10	50
Flight Staging		5	10	50	8	40	7	35	10	50
Autonomy (Flight)		5	5	25	5	25	5	25	6	30
Autonomy (Development)		5	10	50	10	50	10	50	8	40
Ground Maintainability		7	10	70	8	56	9	63	9	63
Ground Handling		6	9	54	7	42	8	48	10	60
Support Equip Req		6	9	54	7	42	8	48	9	54
Risk										
Schedule		9	9	81	9	81	9	81	7	63
Costs		9	9	81	8	72	8	72	8	72
Performance & Capability		9	9	81	8	72	8	72	8	72
Spacecraft Effect										
Tug Length		5	9	45	5	25	8	40	9	45
Spacecraft Design Changes		5	8	40	8	40	8	40	9	45
Evolutionary & Growth Cap.										
Incorporated (Phased)										
Potential		5	9	45	9	45	9	45	8	40
TOTALS		100%	156	916	137	808	131	786	151	874
Technical Factors	Score		100		88		86		95	
	Rating		Good		Poor		Poor		Fair	

Figure 2.3-5 Example of Candidate Selection Matrix for Unquantifiable Factors

Table 2.3-7 Basic Vehicle Configuration Comparison

Single Stage	Two Stage	Stage-and-a-Half
Simplest design	Each stage requires higher than 0.97 reliability	Requires drop-tank staging & separation mechanism
Least manufacturing cost	Optimum performance requires complex trapeze mode	Debris in space
Simplest abort	More complex Orbiter interface	Propellant loading more difficult
Fixed engine nozzle	Ground checkout, maintenance & test doubled	Abort dumping more difficult
Simplest thermal control	Retractable engine nozzle required	Greatest leak potential (6 disconnects)
Simplest flight operations	Software more complex	Reliability achievement more difficult
Simplest ground operations	Propellant loading more difficult	Length sacrifices some spacecraft-carrying flexibility
Reliability easiest to achieve	Abort dumping more complex	Complex plumbing
More length available for spacecraft/multiple spacecraft	Requires intervehicle staging & mech[illegible]	Potential stability problem in handling
Least leak potential	Length sacrifices spacecraft-carrying flexibility	More GSE
Less GSE	Req[illegible] common bulkheads	
	Leak potential doubled	
	More ground handling required	
	Most GSE	
Recommended - Single stage over multiple stage		

c. OME versus Bell Engine - The OME is recommended over the Bell engine even though they are essentially equal in cost and performance because of:

- More options (low-thrust mode, high-thrust mode, phase develop without concern for tank sizing to match different mixture ratio);

- Lower thrust (step thrust not required);

- Commonality with Shuttle;

- No additional propellant logistics required (no silicon additives).

d. Solar-Array Power versus Batteries and Fuel Cells - It was determined that solar-array power was preferred over battery systems and fuel cell systems because of:

- Longer mission duration for equal weight;

- No cryogenic servicing.

2.3.3.5 <u>Selection Methods</u> - The basic approach to selection of the preferred candidates in each capability option was to generate a tabular display of pertinent data about each configuration, and then to go through a deductive reasoning process to establish the most desirable selection. Each configuration for which these data were generated met the imperatives criteria previously discussed—each can meet mission objectives in a safe, reliable manner. The comparison that remained was in the areas of cost (development, investment, and operational) and technical margins.

Development cost is seen as particularly critical for the Shuttle program because early-year funding will cause an undesirable peak in fiscal planning. Investment, the cost of producing the Tug fleet, tends to increase the peak early-year funding and is, therefore, also critical. Operations cost and total program cost were considered important, but their criticality was not as well understood as early-year spending.

Technical margins are more subjective selection criteria than cost. Two basic thoughts are given weight. First, a performance margin was desirable. The configuration performance descriptive data, while consistent relative to each other, were not considered reliable in an absolute sense. Second, the technical factor rating (para 2.3.3.3) was considered a significant discriminator in cases in which cost and performance parameters were close.

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Tables 2.3-8, 9, and 10 illustrate how the selection of configuration IA2-8 was made for Capability Option 1. First, as shown in Table 2.3-8, flight programs associated with each configuration as applied to the mission model for each capability option were developed. From this, fleet size, production and operation cost could be derived. The array of selection data for each configuration is summarized in Table 2.3-9. Basic selection data are shown above the double line, summary data about the flight program and selected transportation indexes are shown below. The sequence of deductive logic leading to selection of Configuration IA2-8 is summarized in Table 2.3-10. Similar selection data were developed and evaluated for each capability option and reported in *Program Concept Evaluation* (Ref 5.5).

Table 2.3-8 Example of Capability Option 1 Mission Capture Summary

Parameter	Tug Configuration Designator						
	1A2-8	IIIC-2	IVT-2	1A1-1	1A2-1	1A2-11	1A3-1
Available spacecraft length, ft(m)	32 (9.8)	26 (7.9)	29 (8.8)	32 (9.8)	32 (9.8)	32 (9.8)	32 (9.8)
Geostationary del cap, lb (kg)	6300 (2857)	5600 (2540)	7300 (3311)	4300 (1950)	5300 (2404)	3900 (1769)	4700 (2132)
Geostationary ret cap w/o kick stage, lb (kg)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Geostationary ret cap w kick stage, lb (kg)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Geostationary R/T cap, lb (kg)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
No. of Shuttle Flights							
Geostationary	110	118	116	117	110	121	115
Mid & polar	115	115	115	115	115	115	115
Planetary	22	20	22	20	20	20	20
Total	247	253	253	252	245	256	250
Spacecraft req 2 flights each	8	10	8	10	10	10	10
Reusable kick stage required	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Deliver MKI-1 required	4	4	4	4	4	4	4
Deliver AKM-1 required	19	17	19	17	17	17	17
Total flights for 100% capture	263	273	273	272	265	776	270

Del Cap - Delivery Capability
Ret Cap - Retrieval Capability
R/T Cap - Round-Trip Capability

Table 2.3-9 Example of Capability Option 1 Tug Candidate Comparison

Tug Candidate	1A2-8	IIIC-2	IVT-2	1A1-1	1A2-1	1A2-11	1A3-1
Spacecraft delivery, geostationary, lb (kg)	6300 (2857)	5600 (2540)	7300 (3311)	4300 (1950)	5300 (2404)	3900 (1769)	4700 (2132)
DDT&E, $M	243.9	238.6	253.6	239.6	239.6	231.6	229.6
Investment, $M	109.7	190.6	140.0	101.3	100.2	97.8	101.3
Operations, $M	266.4	426.8	279.7	266.4	266.4	263.4	266.4
Cost/flight, $M	0.964	1.583	1.076	0.963	0.940	0.926	0.943
Total program cost, $M	3309	3605	3418	[illegible]	3319	3433	3377
Technical factors	Good	Poor	Poor	Good	Good	Good	Good
No. of flights	263	273	269	272	265	276	270
No. of kick stages	23	21	23	21	21	21	21
Total tug cost, $M	548	739	593	[illegible]	536	535	542
DDT&E $/lb ($/kg) del	36.7 (83.3)	46.2 (101.9)	34.7 (76.5)	55.7 (122.8)	45.2 (99.7)	59.4 (131.0)	48.9 (107.8)
DDT&E $/lb ($/kg) ret	---	---	---	---	---	---	---
Launch $/lb ($/kg) del	0.153(0.339)	0.283(0.624)	0.247(0.324)	0.219(0.483)	0.177(0.390)	0.237(0.523)	0.201(0.443)
Launch $/lb ($/kg) ret	---	---	---	---	---	---	---
(Launch $/lb x DDT&E (Launch $/kg x DDT&E $) $	37.3 (82.2)	73.1 (161.7)	37.4 (82.5)	52.5 (115.8)	42.5 (93.7)	55.0 (121.3)	46.1 (101.7)

Table 2.3-10 Configuration Selection Summary

<u>Capability Option 1 - 1979 Delivery Only</u>

Comparison - single-stage/two-stage/stage-and-a-half

Early investment, total program costs, & technical factors indicate single-stage preferred

<u>Single-Stage Factors</u>

IA2-8 vs other single stages

Best performing single-stage candidate; therefore least performance risk

DDT&E & cost/flight same (within accuracy)

Length is shortest

IA2-11

Battery power system limits mission to 2 days

IA3-1

Longer vehicle than IA2-8 (engine), marginal thrust but lowest DDT&E option

<u>Conclusion</u> - IA2-8 Recommended

High spacecraft capability, i.e., largest performance margin & most mission flexibility

Shortest vehicle

Titanium (preferred over aluminum)

Lowest total program cost

Other cost differences negligible

2.3.4 Preferred Candidates

Configurations selected as the best candidates to fulfill the requirements of the seven capability options (para 2.3.1.2) are shown in Table 2.3-11. Note that they are all single-stage configurations with isolated tanks, and all feature titanium plus composite construction. The simplicity and inherent reliability and safety of this design overbalances the modest performance improvements of more sophisticated stage arrangements. Titanium/composite structure improves performance with no operational penalty and with only minor development and build cost increase. Two engine selections are made: (1) an uprated OME for modest performance goals, early availability, and low development cost, (2) a new Class I engine for improvement performance with increased development cost. Also, two avionics configurations were selected: (1) an early technology level with delivery-only capability, and (2) a more advanced technology level with spacecraft retrieval capability.

Table 8.3-11 Summary of Preferred Tug Candidates by Capability Option

Capability Option	Preferred Tug	Configuration	Material	Engine	Avionics
1	IA2-8	Single-stage, isolated tanks	Ti & composite	OME uprated	AV-1, delivery-only
2	IA2-8,7	Single-stage, isolated tanks	Ti & composite	OME uprated	AV-1 & AV-4, delivery & retrieval
3	IA2-8 to -4,3	Single-stage, isolated tanks	Ti & composite	OME uprated to new Class I	AV-1 to AV-3 & AV-2, delivery-only to delivery & retrieval
4	IA2-4,3	Single-stage, isolated tanks	Ti & composite	New Class I	AV-3 & AV-2, delivery & retrieval
5	IA2-8 to -4,3	Single-stage, isolated tanks	Ti & composite	OME uprated to new Class I	AV-1 to AV-3 & AV-2, delivery-only to delivery & retrieval
6	IA2-8,7 to -4,3	Single-stage, isolated tanks	Ti & composite	OME uprated to New Class I	AV-1 & AV-4 to AV-3 & AV-2, delivery & retrieval to delivery & retrieval
7	IA2-4,3	Single-stage, isolated tanks	Ti & composite	New Class I	AV-3 & AV-2, delivery & retrieval

Capability Option	Preferred Tug	Performance Del/Ret (Geostationary), lb(kg)	DDT&E, $M	Investment, $M	Operations, $M	Cost/Flt, $M	Total Program Cost, $M
1	IA2-8	6300/NA(2857/NA)	244	110	266	0.96	3309
2	IA2-8,7	6300/1230(2857/558)	274	121	268	1.00	6124
3	IA2-8 to -4,3	7800/2300(3537/1043)	337	121	268	1.00	5449
4	IA2-4,3	7800/2300(3537/1043)	300	121	268	1.00	4179
5	IA2-8 to -4,3	7800/2300(3537/1043)	337	121	268	1.00	5564
6	IA2-8,7 to -4,3	7800/2300(3537/1043)	343	121	268	1.00	5725
7	IA2-4,3	7800/2300(3537/1043)	300	121	268	1.00	4179

One of the contractor requirements at this juncture in the study was to recommend Tug family options that merited more in-depth study. The most important considerations were the:

- Baseline Option 1, delivery-only case;
- Effect of delayed IOC;
- Effect of retrieval capability;
- Effect of phased development;
- Effect of minimum-development-cost selections;
- Effect of direct development of advanced capability.

The array of Tug family options in Table 2.3-12 illustrates these considerations, and was Martin Marietta's recommendation for further study.

After evaluation of contractor recommendations, NASA assigned Martin Marietta the following final options as the most significant for further study:

- Final Option 1 - Minimum development cost with delivery-only capability.
- Final Option 2 - Direct development of advanced capability with a later IOC.
- Final Option 3 - Phase development
- Final Option 3A - Same as Final Option 3, except with stage-and-a-half vehicles.

The detailed definition of these final options is in paragraph 2.4.

Table 2.3-12 Recommended Tug Family Options for Further Study

Family Option	Preferred Tug	IOC Date	Requirements	Remarks
1	1A2-8 + KS	1979, Direct	Delivery only	Option 1 winner
2	1A2-8 + KS	1983, Direct	Delivery only	Additional proposed option, min funding, 1970s
3	1A2-8,7 + KS	1983, Direct	Delivery & retrieval	Will show transportation cost of retrieval when compared to 2
4	1A2-8 to 4,3 + KS	1979, 1983, Phased	Delivery in 1979 Delivery & retrieval in 1983	Will show phase development when compared to 1, 3 & 6
5	IA3-1 + KS	1983, Direct	Delivery only	Lowest DDT&E option
6	1A2-4,3 + KS	1983, Direct	Delivery & retrieval	Best Tug configuration needed for phase development comparison

2.4 PROGRAM DEFINITION

In summary, this section discusses Space Tug requirements and selected Tug configurations for Final Options 1, 2, 3 and 3A, which evolved from the original "seven capability options" or "7 Buckets" discussed in paragraph 2.3.

2.4.1 Final Option 1

2.4.1.1 Option Definition - The Final Option 1 space vehicle is a reusable direct-developed Tug with no built-in growth capability, designed for a maximum mission duration of 36-hr, and is scheduled for IOC in late December 1979 at ETR. Mission requirements include delivery-only capability into the geostationary orbit of currently designed expendable spacecraft, or multiples thereof, weighing 3500 lb (1588 kg) or less.

2.4.1.2 Configuration - The selected space vehicle that meets Final Option 1 requirements is a reusable single-stage vehicle, designated Final Option 1, Interim Tug (IA3-2). It is designed for a 36-hr maximum, delivery-only mission, and is capable of placing a 3800-lb (1724-kg) spacecraft in geostationary orbit. An inboard profile is shown in Fig. 2.4-1 and -2.

On certain planetary missions, the Interim Tug is combined with one of three auxiliary kick-stage arrangements (para 2.2.11): one with 10,000 lb (4536 kg) of propellants, one with 1500 lb (680.4 kg), or a combination of the two. In all cases, the kick stages are expended and the Tug is returned to the Orbiter. In addition, for some planetary missions, the Tug must also be expended. expended.

The Interim Tug is direct-developed for IOC in late December 1979 at ETR with no special built-in growth capabilities. It is capable of operating within the specified environment at Autonomy Level II and reliability of 0.97. There is no power furnished to the spacecraft.

The vehicle is 27 ft 7 in. long (8.41 m) from the forward face of the separation module (not shown) to the aft end of the engine bell, with a dry weight (including 10% contingency) of 2886 lb (1309 kg).

The following paragraphs are brief descriptions of the integrated vehicle subsystems that make up the complete Interim Tug. Detailed subsystem descriptions are in paragraph 2.2. For clarification and continuity in this document, descriptions refer to previously assigned subsystem designators.

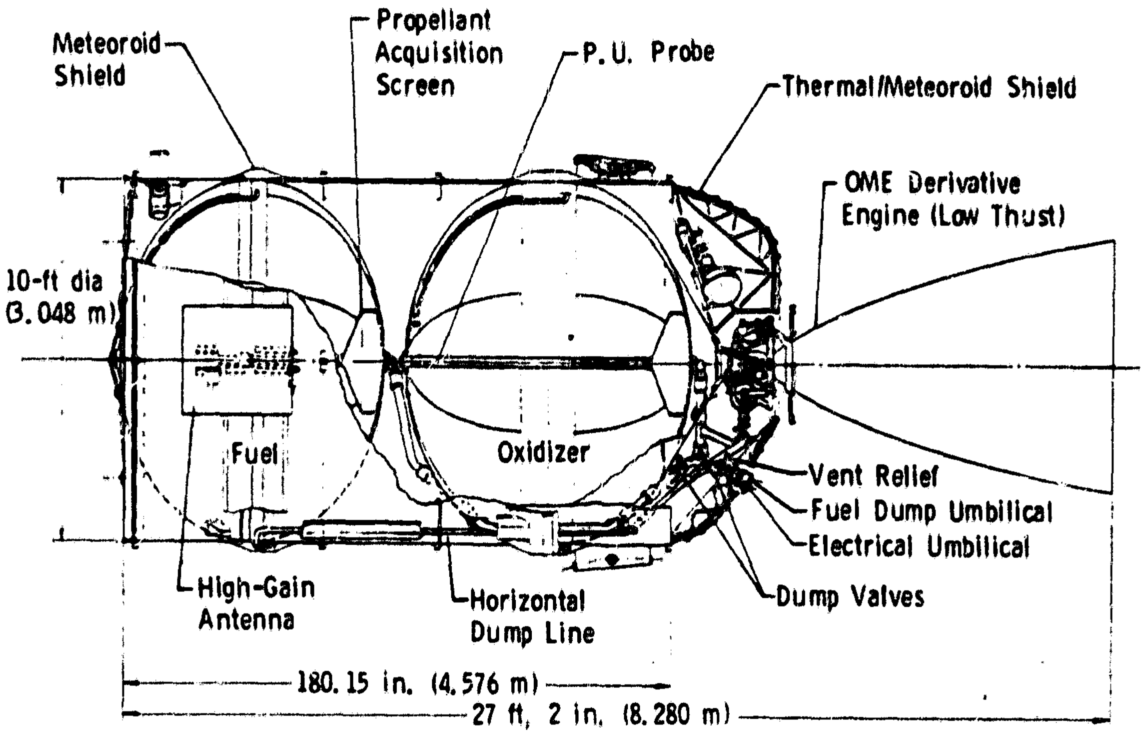


Fig. 2.4-1 Final Option 1 Interim Tug Inboard Profile

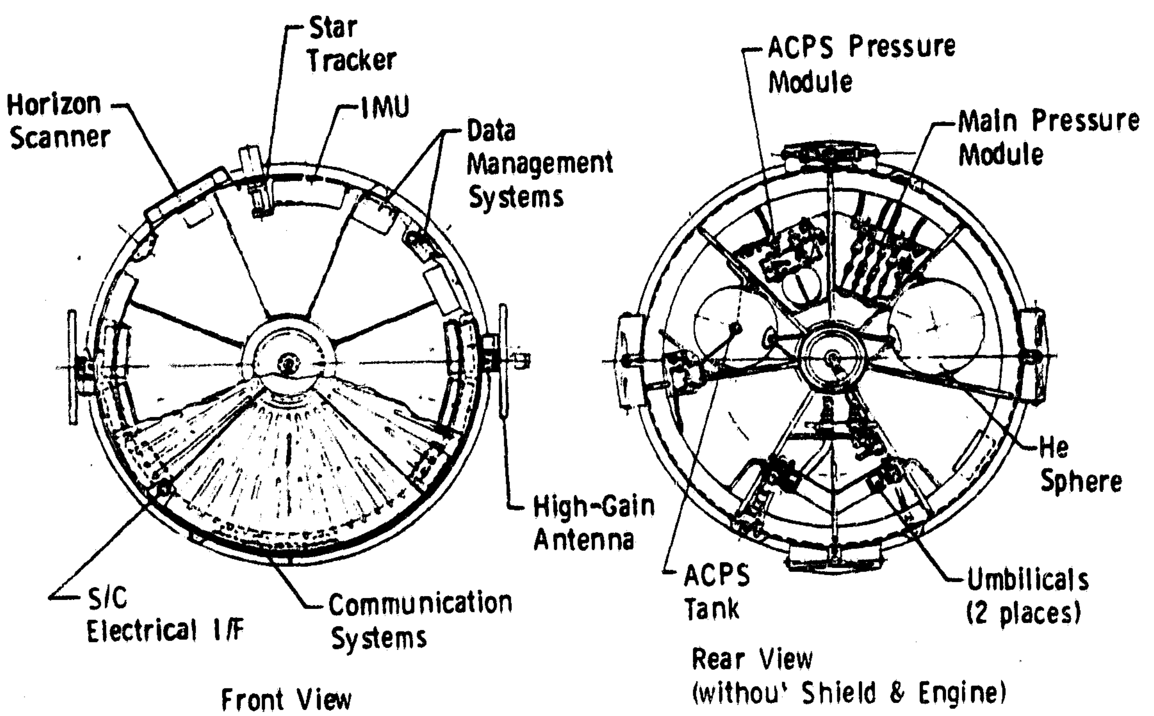


Fig. 2.4-2 Final Option 1 Interim Tug Inboard End Views

2.4.1.2.1 Structure - The Tug structure primarily comprises four elements: propellant tanks, engine compartment, forward equipment compartment, and spacecraft interface.

The propellant tanks are isolated, titanium tanks (fuel forward) with $\sqrt{2}$ elliptical domes, designed for 57,000 lb (25,855 kg) of total propellants at a mixture ratio of 1.9. The tanks are joined by a skirt of composite honeycomb using graphite epoxy face sheets over an aluminum honeycomb core. Radial meteoroid shielding is provided for the portion of each tank not covered by body structure.

The engine compartment skirt is graphite epoxy over an aluminum honeycomb core. The engine thrust cone is titanium.

The forward equipment compartment skirt is aluminum skin-stringer construction. All structural ring frames, hard points, and splices are titanium.

The spacecraft interface is a 10-ft (3.048-m) dia by 5-in. (12.7-cm) deep separation module containing separation ordnance and the spacecraft deployment assembly. Paragraph 2.2.9 provides a detailed description of the module.

2.4.1.2.2 Thermal Control - The thermal control subsystem, designated TH-5, is passive, using thermal paint and multilayer insulation. Special optical solar-reflector material is used at the avionics equipment compartment; radiation shields are applied at the ACPS thrusters; and heat pipes are used between the batteries and forward tank dome. Electric heaters are used for low-temperature-critical components.

2.4.1.2.3 Data Management - The data management subsystem uses a flexible signal interface (FSI) and consists of a central data processor, encrypter/decrypter unit (GFE), branch boxes, and interconnecting cabling. The central processor contains units required for general-purpose and command-data-timing-checkout (CDTC) processing and memory.

2.4.1.2.4 Guidance, Navigation, and Control - A star tracker and skewed redundant IMUs are used for guidance and navigation. Although the Tug is baselined at Autonomy Level II, addition of a horizon sensor would permit upgrading to Autonomy Level I operation. A pair of electrically driven, tandem linear hydraulic actuators is used for pitch and yaw control in powered flight, with roll control obtained from the ACPS thrusters. Attitude in coast flight is controlled solely by the ACPS system.

2.4.1.2.5 Communications - The all-S-Band communications subsystem consists of high-gain antennas and gimbal assemblies, a strip-line omnidirectional antenna, FM and PM transmitters, receivers, power amplifiers, a coupling and switching network and coaxial cable harness.

2.4.1.2.6 Instrumentation - The instrumentation subsystem is not separate but is integral with the FSI data management subsystem, with end-item instrumentation units (pressure transducers, temperature recording controllers, etc) provided by the applicable user and interfacing with applicable FSI branch circuits.

2.4.1.2.7 Electrical Power, Distribution, and Control - The Interim Tug electrical subsystem is battery powered by four 165-A-h main batteries and a 25-A-h auxiliary battery, and uses a two-wire positive and single-wire return distribution system with solid-state remote power controllers and relays. A compatible interface with the Orbiter is provided. Ordnance squibs, detonating blocks, squib firing circuit (SFC), and separation-module detonating cord are parts of the electrical power subsystem.

The data management; guidance, navigation, and control; communications; instrumentation; and power subsystems comprise the Final Option 1 Tug Avionics system. This system is designated AV-9(4).

2.4.1.2.8 Propulsion - The propulsion system consists of the main engine and auxiliary-control propulsion subsystems.

The main engine (GFE) is derived from the OME and uprated to 150 P_c 327-sec I_{sp} (3207 N-s/kg), 7500-lb (33,362-N) thrust and a mixture ratio of 1.9. The main engine support subsystem, designated PR-1(2A), has a regulated helium-ambient-storage propellant pressurization, feed, and dump system designed for vertical loading and horizontal or vertical dumping. The helium sphere is a composite material.

The ACPS, designated ACPS-2(8A), consists of 16 thrusters (four modules) using a monopropellant (hydrazine) with a capability of 62,500-lb-sec (278,014-N-s) impulse, and 3700-psig (2551-N/cm^2) helium as the pressurant.

2.4.1.2.9 Reliability - Interim Tug reliabilities meet or exceed the requirement of 0.97 for all geostationary missions. A detailed description of system and subsystem reliability is in Vol 5.0 of the *Selected Option Data Dump* (Ref 5.8).

2.4.1.3 Mass Properties - Vehicle weights, centers of gravity, and moments of inertia are presented in detail in Vol 5.0 (Ref 5.8). In summary, Interim Tug weights and center-of-gravity travel are:

a. Weight Summary

Item	Weight, lb	kg
Tug dry weight + 10% contingency	2,886	1,309
Structure	1,044	473.6
Thermal control	101	45.8
Avionics	702	318.4
Propulsion	777	352.4
Unusable propellants	218	98.9
Burn-out weight	3,104	1,408
Nonimpulsive expendables	75	34.02
Propellants (usable)	57,023	25,865
First-ignition weight	60,202	27,307
Shuttle interface accommodations	1,650	748.4
Tug mass fraction	0.948	

b. Center-of-Gravity Travel - Center-of-gravity travel with a typical 3500-lb (1588-kg) 25-ft (7.62-m) spacecraft attached remains well within the allowable Shuttle payload cg envelope. Longitudinal and vertical centers of gravity versus allowable evelope are shown in Fig. 2.4-3 and -4, respectively. The lateral falls within 3/4 in. (1.91 cm) of the Shuttle payload-bay centerline.

2.4.1.4 Mission Accomplishments - As used in this report, mission accomplishments cover performance, capture summary, and annual flight summary--all with respect to the mission model.

2.4.1.4 Performance - Performance capabilities of the Final Option 1 Interim Tug are shown in Fig. 2.4-5, with the spacecraft weight plotted versus delta velocity. Performance to various orbital inclinations is shown, as well as performance for the various modes previously discussed. Circles on the plot represent characteristics of the mission model spacecraft. The heavy concentration of points at the 14,000-fps (4267-m/s) velocity represents the geostationary/corridor.

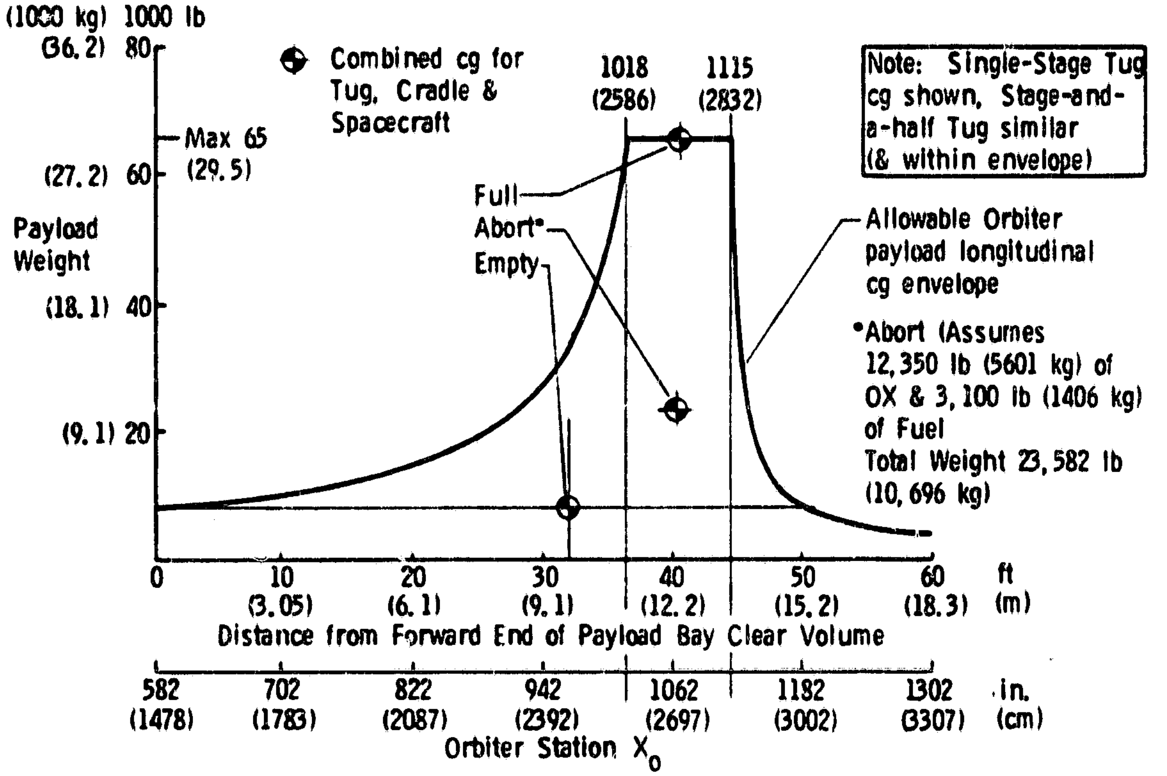


Fig. 2.4-3 Longitudinal Center of Gravity vs Allowable Envelope

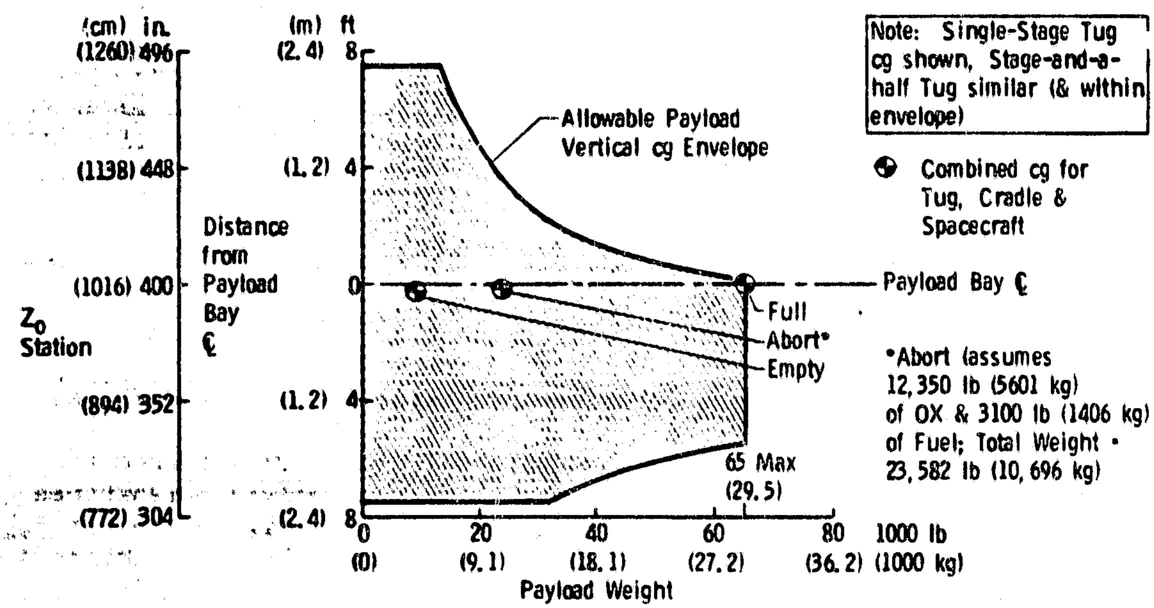


Fig. 2.4-4 Vertical Center of Gravity vs Allowable Envelope

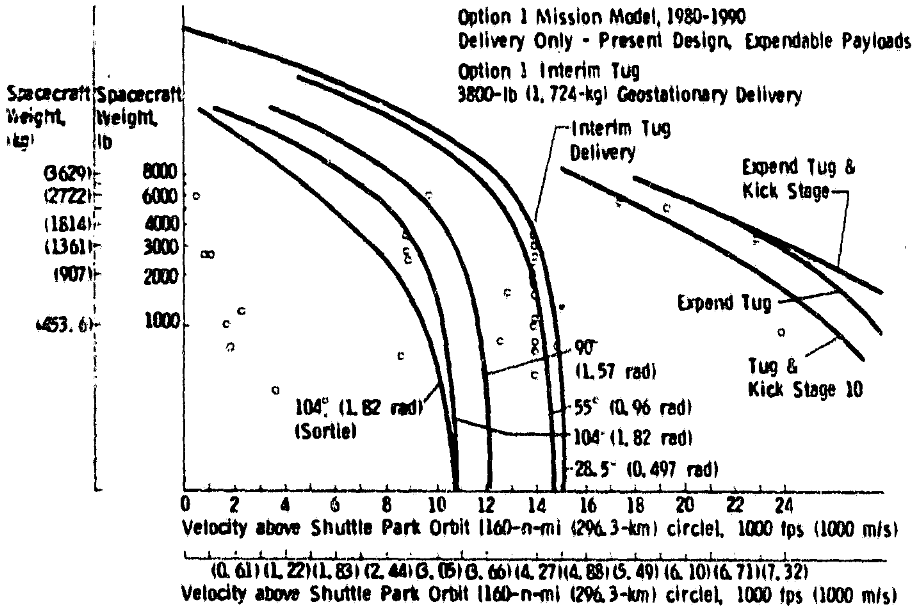


Fig. 2.4-5 Final Option 1 Mission Model and Tug Performance

2.4.1.4.2 <u>100% Capture Summary</u> - A total of 360 current-design expendable spacecraft must be accommodated by the mission model described for Final Option 1 (Vol 4.0 of *Selected Option Data Dump*, Ref 5.8). Applicable mission category, spacecraft user, launch site, and number of spacecraft required by this mission model are:

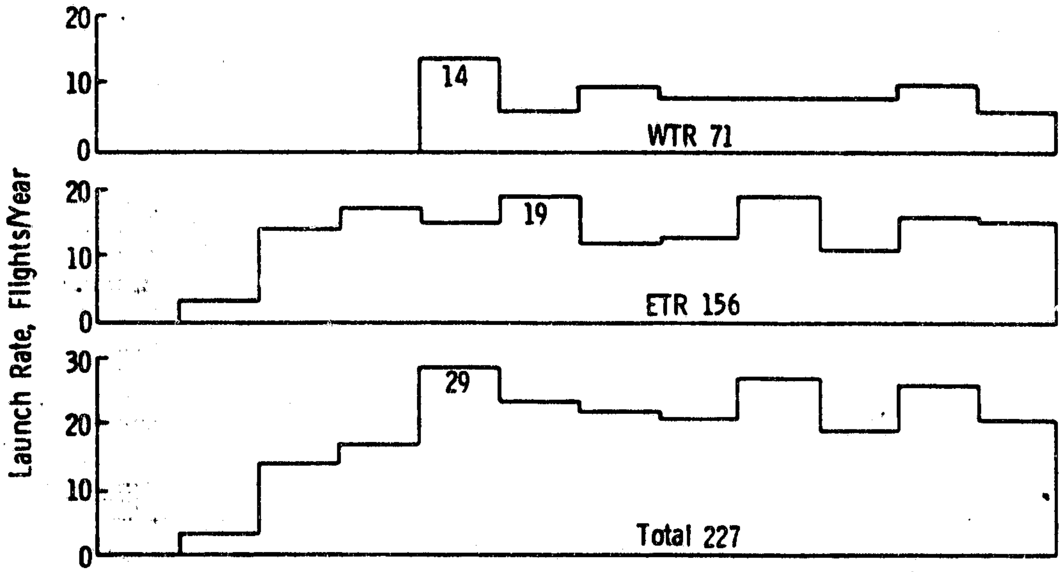
	User/Launch Site				
	NASA		DOD		
Mission Category	WTR	ETR	WTR	ETR	Total Spacecraft
Geostationary	--	123	--	59	182
Midinclination	--	10	48	18	76
Planetary	--	30	--	--	30
Polar	38	--	34	--	72
Totals	38	163	82	77	360

By employing the multiple spacecraft delivery capability, which is within the ground rules of the mission model assessment, the 360 spacecraft can be delivered with 238 flights (100% capture). Flight modes for these 238 flights are:

Flight Modes	User NASA	DOD	Total Flights
Multiples	58	39	97
Singles	49	75	124
Kick stages	7	--	7
Expended Tugs	10	--	10
Totals	122	114	238

The ten expended Tug modes and seven kick-stage modes are required to accomplish the more difficult planetary missions. All other flights are accomplished by the Tug alone, with the Tug returning to the Orbiter.

2.4.1.4.3 Programmatic Flight Summary - Figure 2.4-6 summarizes Tug flights by year and launch site for programmatic considerations. The number of flights in the first year is limited to three by Shuttle availability. Three additional launches are included for reliability losses. This results in 227 flights for programmatic consideration compared to 238 flights required for 100% capture.



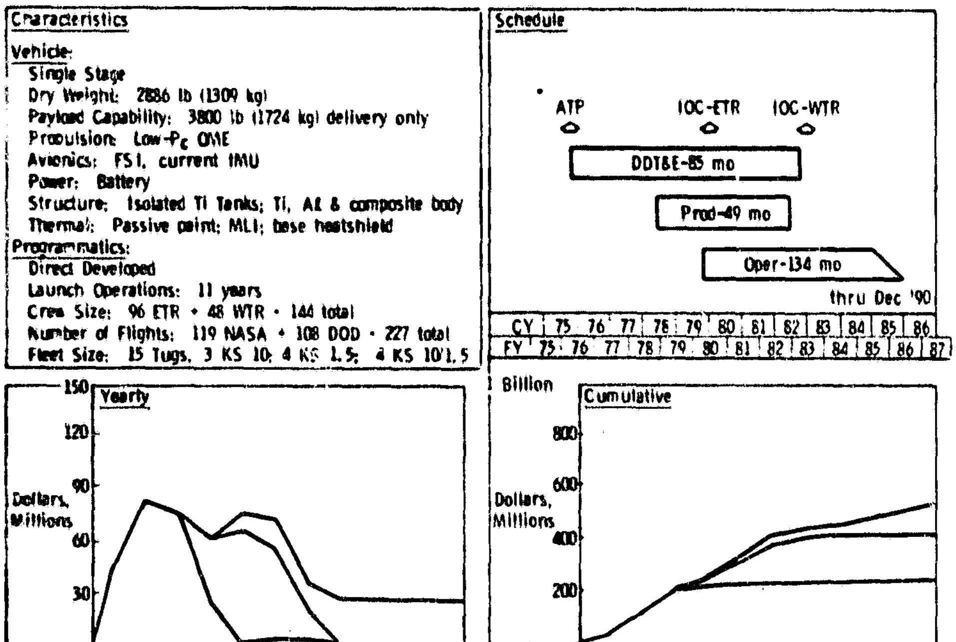
CY	80	81	82	83	84	85	86	87	88	89	90	Total
WTR	0	0	0	14	6	11	8	8	8	10	6	71
ETR	3*	14	18	15	19	12	13	19	12	16	15	156
Total	3*	14	18	29	25	23	21	27	19	26	21	227

*Limited by Shuttle availability

Fig. 2.4-6 Final Option 1 Interim Tug Annual Flight Summary

2.4.1.5 Programmatics

2.4.1.5.1 NASA Programmatics - Programmatics data and results for Final Option 1 are summarized in Fig. 2.4-7. The program is based on completion of preliminary system and subsystem specifications during Phase B and completion of supporting research and technology (SRT) tasks identified for this option in para 2.6 before starting DDT&E.



FY	76	77	78	79	80	81	82	83	84	85	86
DDT&E	46	81	75	26	2	4	2	1			
Prod			1	35	64	50	17				
Oper					8	16	17	23	24	24	23
Total	46	81	76	61	74	70	36	24	24	24	23

FY	76	77	78	79	80	81	82	83	84	85	86	90
DDT&E	46	127	202	[illegible]	230	234	236	237	237	237	237	237
Prod			1	37	100	149	166	166	166	166	166	166
Oper					8	25	42	65	89	113	136	242
Total	46	127	[illegible]	264	338	408	444	468	492	516	539	645

Fig. 2.4-7 Final Option 1 Programmatics Summary

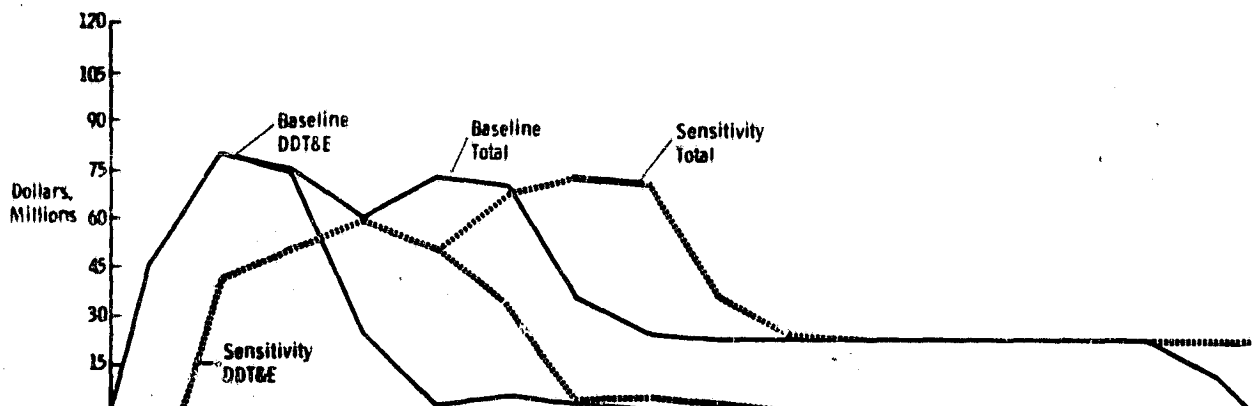
Because no kick stages are required before 1982, basic engineering is delayed until near completion of main-stage engineering. Production of main and kick stages is planned for concurrent completion.

The first Tug is built during DDT&E, and the remaining 14 are built during production. Because an operational spacecraft is planned for the first launch, the operations program starts two months before first launch.

Fifteen main stages and 11 expendable kick stages are used for 227 flights. Ten main stages are expended and three are lost due to reliability problems. Shuttle availability limits the number of flights in 1980 to three.

The Final Option 1 Tug program schedule and associated planning discussion are in Vol 8.0, Sect. I, para 1.0, and Sect. II, para 7.0 of *Selected Option Data Dump* (Ref 5.8). Detailed program cost data are in Vol 8, Sect. II, and the appendix to Vol 8.0.

2.4.1.5.2 IOC Sensitivity - An IOC sensitivity study was conducted in which IOC dates for ETR and WTR were delayed two years. Results are presented in Fig. 2.4-8.



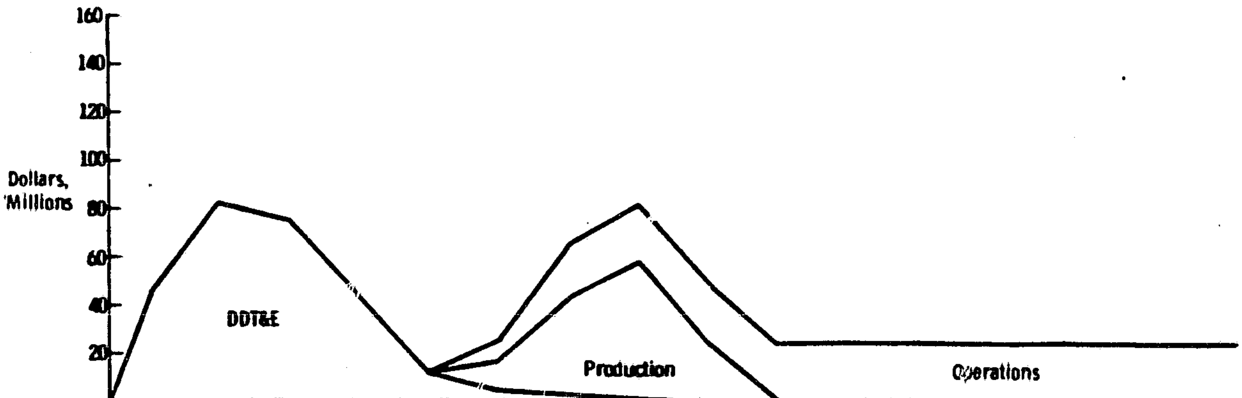
	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91
DDT&E																
Baseline	45.8	81.4	74.5	25.7	2.2	4.0	2.7	0.5								
Sensitivity		41.0	50.2	60.0	50.0	32.7	2.2	4.0	2.7	0.5						
Total																
Baseline	45.8	81.4	75.7	60.7	73.9	70.3	36.4	24.1	23.8	23.5	23.4	23.6	23.4	23.6	23.6	11.7
Sensitivity		41.0	50.2	60.0	51.4	67.7	73.9	70.3	36.4	24.1	23.8	23.5	23.4	23.6	23.4	23.6

Fig. 2.4-8 Final Option 1 Cost Sensitivity and Funding Requirements for Dec 1981 IOC

Delaying IOC two years reduces yearly peak funding requirements for DDT&E from $81.4 million in FY 1977 to $60.0 million in FY 1979, providing a more reasonable funding distribution. Total DDT&E costs are increased by $6.5 million due to the program stretch-out.

Additional details are presented in Vol 8.0, Sect II, para 8.0 of the *Selected Option Data Dump* (Ref 5.8).

2.4.1.5.3 <u>DOD Programmatics</u> - The major impact of DOD programmatics results from delaying the DOD production decision (DSARC III) until substantial operational test and evaluation (OT&E) data are available. This reduces potential modification requirements during production and deployment phases and provides operations experience for projecting fleet size and operations program costs. However, this delays production expenditures, resulting in uneven funding distribution, as shown in Fig. 2.4-9.



FY	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91
Dev	46.9	83.5	75.2	42.4	11.9	5.4	3.0	0.4								
Prod						12.5	48.8	57.7	23.4							
Depl						9.3	13.7	23.3	25.5	24.8	24.6	25.1	24.6	25.0	25.0	13.1
Total	46.9	83.5	75.2	42.4	11.9	27.2	65.5	81.4	48.9	24.8	24.6	25.1	24.6	25.0	25.0	13.1

Fig. 2.4-9 Final Option 1 Funding Requirements for DOD Programmatics

Assessment of DOD programmatics is summarized in paragraph 3.3. Schedule and cost data are presented in Vol 8.0, para 12.0 of the *Selected Option Data Dump* (Ref 5.8); a comparison of DOD and NASA schedules is presented in paragraph 1.0.

2.4.1.6 <u>Sensitivity Studies</u> - Only the electrical-power-to-spacecraft sensitivity study was performed specifically for the Final Option 1 Interim Tug. As identified in Vol 5, Sect. II, of *Selected Option Data Dump* (Ref 5.8), it was determined that effects of supplying 300 watts to the spacecraft would drive the Tug power system concept to solar arrays rather than the present battery power system, and would result in a spacecraft penalty of 425 lb (193 kg).

2.4.2 Final Option 2

2.4.2.1 Option Definition - The Final Option 2 space vehicle is similar to Final Option 1 only in that it is also a reusable direct-developed Tug. The Final Option 2 vehicle, designed for a maximum mission duration of 7 days, contains built-in growth capability for retrieval as well as delivery-only missions, and is scheduled for IOC in late December 1983 at ETR. Final Option 2 mission requirements include delivery-only capability of 3500 lb (1588 kg) or less, and a retrieval capability up to 3500 lb (1588 kg).

2.4.2.2 Configuration - A reusable single-stage space vehicle designated Final Option 2, Direct-Developed Tug-Delivery (IA2-4)/Retrieval (IA2-3) was selected to meet Final Option 2 requirements. It is designed for 7-day delivery-only missions, accompanied by kits designed to permit delivery/retrieval missions and delayed retrieval flight mode (DRFM) missions. Basic geostationary orbit capabilities are:

Delivery only (IA2-4)	6000 lb (2722 kg)
Retrieval only (IA2-3)	1800 lb (816.5 kg)
Retrieval only-DRFM (IA2-3)	3500 lb (1588 kg)

For an expansion of Final Option 2 Tug performance and flight modes, see Vol 5.0 of the *Selected Option Data Dump* (Ref 5.8)

On certain planetary missions, the vehicle is combined with one of two auxiliary kick-stage arrangements (para 2.2.11): one kick-stage with 10,000 lb (4,536 kg) of propellants, or one that combines this with a 1500-lb (680.4-kg) propellant kick stage.

The basic vehicle is direct-developed for IOC in late December 1983 at ETR. It is capable of operating within the specified environment at Autonomy Level II and reliability of 0.97.

The delivery-only vehicle (Fig. 2.4-10 and -11) has a length of 27 ft 4 in. (8.33 m) from the forward face of the separation module (not shown) to the aft end of the engine bell, and has a dry weight (including 10% contingency) of 2750 lb (1247 kg).

For the retrieval mode, the configuration shown in Fig. 2.4-10 and -11 is 28 ft 8 in. (8.74 m) from the forward face of the docking mechanism (not shown) to the aft end of the engine bell. It has a dry weight (including 10% contingency) of 2983 lb (1353)kg)

The following paragraphs are brief descriptions of the integrated vehicle subsystems that make up the complete Final Option 2 Tug. Detailed subsystem descriptions are in paragraph 2.2. For clarification and continuity in this document, the following descriptions refer to previously assigned subsystem designators.

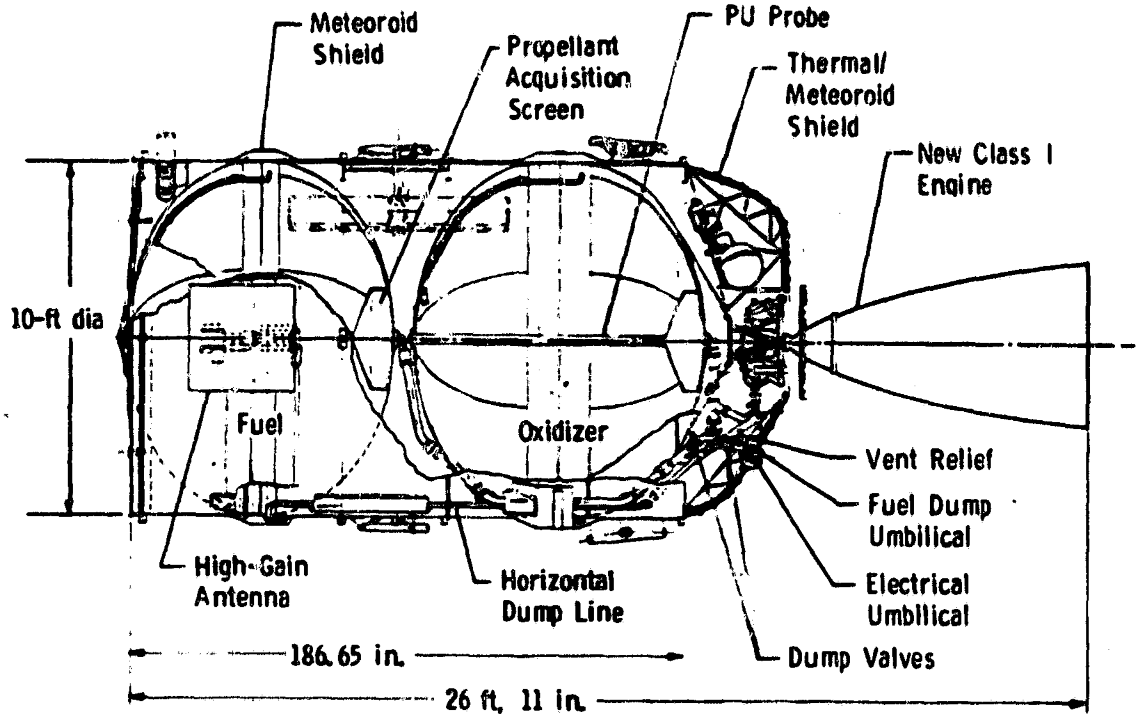


Fig. 2.4-10 Final Option 2 Direct-Developed Tug Delivery/Retrieval Inboard Profile Inboard Profile

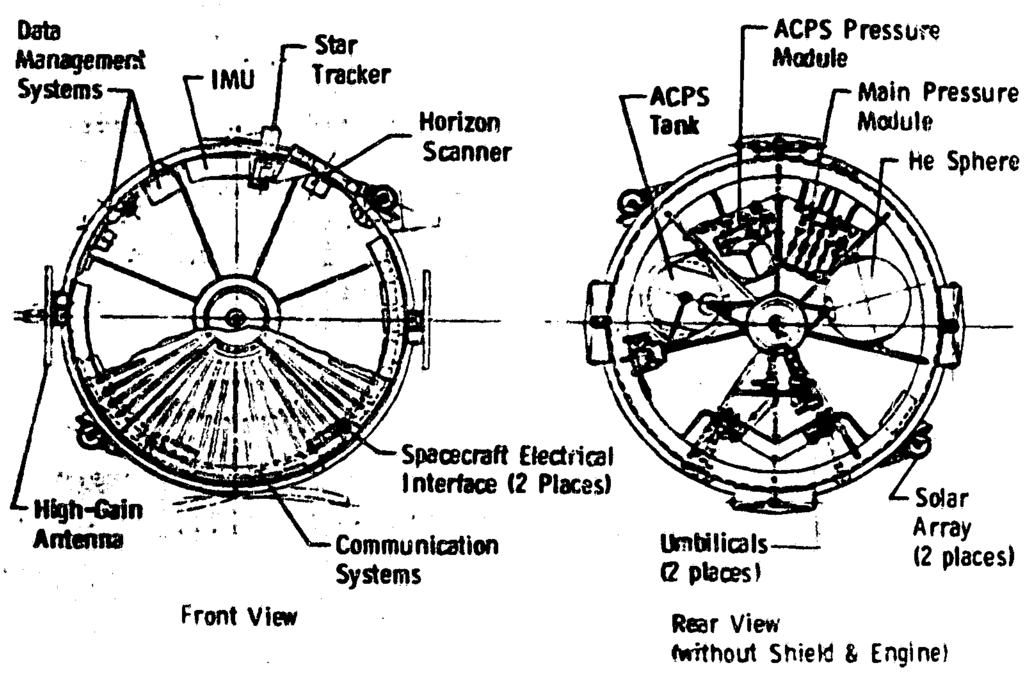


Fig. 2.4-11 Final Option 2 Direct-Developed Tug Delivery/Retrieval Inboard End Views

2.4.2.2.1 Structure - The Tug structure primarily comprises four elements: propellant tankage, engine compartment, forward equipment compartment, and spacecraft interface.

The propellant tanks are isolated, titanium tanks (fuel forward) with $\sqrt{2}$ elliptical domes, designed for 60,000 lb (27,216 kg) of total propellants at a mixture ratio of 1.9. The tanks are joined by a skirt of composite honeycomb using graphite epoxy face sheets over an aluminum honeycomb core. Radial meteoroid shielding is provided for the portion of each tank not covered by the body structure.

The engine compartment skirt is graphite epoxy over an aluminum honeycomb core. The engine thrust cone is titanium.

The forward equipment compartment skirt is aluminum skin-stringer construction. All structural ring frames, hard points, and splices are titanium.

The spacecraft interface for the delivery-only mode is a 10-ft (3.048-m) dia by 5-in. (12.7-cm) deep separation module containing separation ordinance and the spacecraft deployment assembly. Paragraph 2.2.9 provides a detailed description of the module. The spacecraft interface for the rendezvous and docking mode is a 10-ft (3.048-m) by 21-in. (53.34-cm) deep docking module containing the docking mechanism, scanning laser radar unit, and video subsystem. This unit also has spacecraft deployment capability for use in the delayed retrieval flight mode (DRFM) for deploying a replacement spacecraft. The docking module is discussed in detail in paragraph 2.2.10.

2.4.2.2.2 Thermal Control - As in the Final Option 1 configuration, the thermal control subsystem, designated TH-5, is passive, using thermal paint and multilayer insulation. Special optical solar-reflector material is used at the avionics equipment compartment; radiation shields are applied at the ACPS thrusters; and heat pipes are used between the batteries and forward tank dome. Electric heaters are used for low-temperature-critical components.

2.4.2.2.3 Data Management - The data management subsystem, common to all Tugs, uses a flexible signal interface (FSI) and consists of a central data processor, encrypter/decrypter unit (GFE), branch boxes, and interconnecting cabling. The central processor contains units required for general-purpose and command-data-timing-checkout (CDTC) processing and memory.

2.4.2.2.4 Guidance, Navigation, and Control - For the delivery only capability, a star tracker and skewed redundant IMUs are used for guidance and navigation. Rendezvous and docking capability is achieved by adding a scanning laser radar (SLR) and video subsystem (mounted in the spacecraft interface rendezvous and docking module). Although the Tug is baselined at Autonomy Level II, addition of a horizon sensor would permit upgrading to Autonomy Level I operation.

A pair of electrically driven, tandem linear hydraulic actuators is used for pitch and yaw control in powered flight, with roll control obtained from the ACPS thrusters. Attitude in coast flight is controlled solely by the ACPS.

2.4.2.2.5 Communications - The all-S-band communications subsystem, common to all Tugs, consists of high-gain antennas and gimbal assemblies, a strip-line omnidirectional antenna, FM and PM transmitters, receivers, power amplifiers, a coupling and switching network and coaxial cable harness.

2.4.2.2.6 Instrumentation - The instrumentation subsystem is not separate but is integral with the FSI data management subsystem, with end-item instrumentation units (pressure transducers, temperature recording controllers, etc) provided by the applicable user subsystem and interfacing with the applicable FSI branch circuit.

2.4.2.2.7 Electrical Power, Distribution, and Control - The Final Option 2 Tug electrical power subsystem is a deployable solar-array/Ag-Zn battery system consisting of redundant flexible roll-out/retractor solar-panel assemblies attached to the vehicle by panel-orientation mechanisms with two-axis freedom, redundant charger/load-regulator units, Ag-Zn 165-A-h main and 25-A-h auxiliary storage batteries, power distributors, wiring, and connectors. The distribution system uses a two-wire positive and single-wire return and has solid-state remote power controllers and relays. Solar panels and orientation assemblies are g-limited and must be retracted during main-engine burns.

In the delivery-only vehicle, ordnance squibs, detonating blocks, squib firing circuit (SFC) and separation-module detonating cord are parts of the electrical power subsystem.

The data management; guidance, navigation, and control; communications; instrumentation; and power subsystems comprise the Final Option 2 Tug avionics system. The system for the delivery-only vehicle is designated AV-3. When rendezvous and docking capability is added to the vehicle, the avionics designator becomes AV-2 (and the vehicle becomes the retrieval version).

2.4.2.2.8 Propulsion - The propulsion subsystem consists of the main engine and auxiliary-control propulsion subsystems.

The main engine is a new Class I, 800-P_c engine (GFE) with 338-sec I_{sp}, (3315 N-s/kg) 12,000-lb (53,379-N) thrust and a mixture ratio of 1.9. The main engine support system, designated PR-1 (2B), has a regulated helium-ambient-storage propellant pressurization, feed, and dumping system that permits horizontal or vertical dumping.

The ACPS, designated ACPS-2 (8C) for the delivery-only configuration, consists of 16 thrusters (four modules) using a monopropellant (hydrazine) with a capability of 62,500-lb-sec (278,014-N-s) impulse, and 3700-psig (2551-N/cm^2) helium as the pressurant. For rendezvous and docking, the system total impulse is increased to 125,000 lb-sec (556,028-N-s) by use of a larger tank, and is designated ACPS-2 (8B).

2.4.2.2.9 Reliability - Final Option 2 Tug reliabilities meet or exceed the requirement of 0.97 for all missions, with or without kick stages. A detailed description of system and subsystem reliability is in Vol 5.0 of the *Selected Option Data Dump* (Ref 5.8).

2.4.2.3 Mass Properties - Vehicle weights, centers of gravity, and moments of inertia are presented in detail in Vol 5.0 (referenced above). In summary, Final Option 2 Tug weights and center-of-gravity travel are:

a. Weight Summary

	Delivery-Only Tug		Retrieval Tug	
Item	Weight, lb	kg	Weight, lb	kg
Tug dry weight + 10% contingency	2,750	1,247	2,982	1,353
Structure	1,063	482.2	1,176	533.4
Thermal control	101	45.8	101	45.8
Avionics	593	269	669	303.4
Propulsion	743	337	765	347
Unusable propellants	220	99	251	113.8
Burn-out weight	2,970	1,347	3,233	1,466
Nonimpulsive expendables	50	22.7	50	22.7
Propellants (usable)	60,049	27,238	60,319	27,360
First-ignition weight	63,069	28,608	63,602	28,849
Shuttle interface accommodation	1,650	748.4	1,650	748.4
Tug mass fraction	0.953		0.949	

2. *Center-of-Gravity Travel* - Center-of-gravity travel with a typical 3500-lb (1588-kg) 25-ft (7.62-m) spacecraft attached remains well within the allowable Shuttle payload cg envelope. The longitudinal and vertical centers of gravity versus allowable envelope are shown in Fig. 2.4-3 and -4, respectively. The lateral cg falls within 3/4 in. (1.91 cm) of the Orbiter payload-bay centerline.

2.4.2.4 Mission Accomplishments - As used in this report, mission accomplishments cover performance, capture summary, and annual flight summary--all with respect to the mission model.

2.4.2.4.1 Performance - Performance capabilities of the Final Option 2 delivery and retrieval Tugs are shown in Fig. 2.4-12, with spacecraft weight versus delta velocity. Performance to various orbital inclinations is shown, as well as performance for the various modes previously discussed. Circles on the plot represent characteristics of the mission model spacecraft. The heavy concentration of points at the 14,000-fps (4267 m/sec) velocity represents the geostationary corridor.

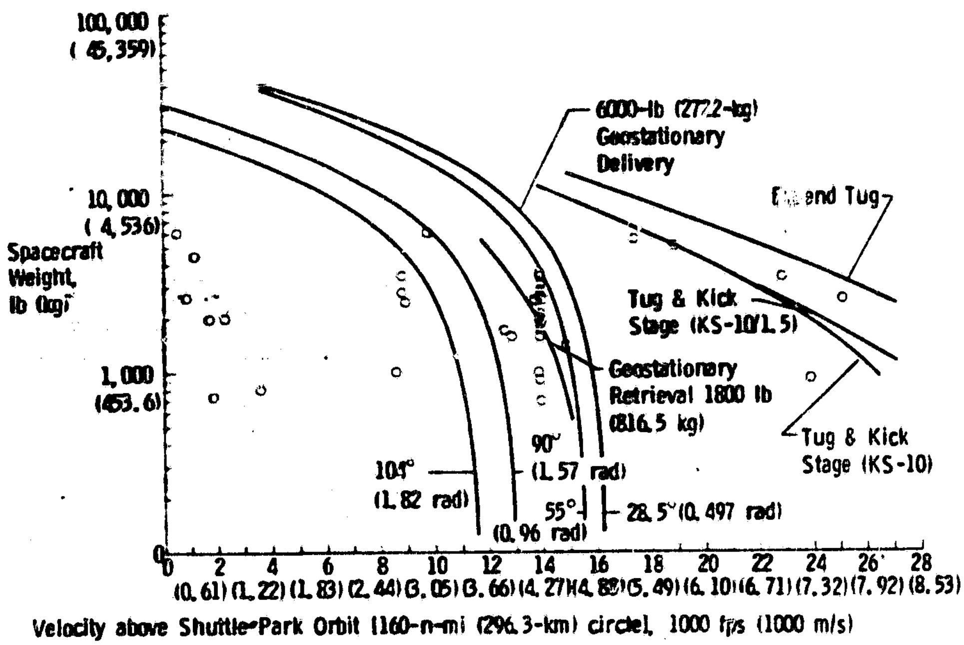


Fig. 2.4-12 Final Option 2 Mission Model and Tug Performance

2.4.2.4.2 100% Capture Summary - A total of 437 spacecraft must be accommodated by the Final Option 2 mission model described in Vol 4.0 of the *Selected Option Data Dump* (Ref 5.8). Final Option 2 consists of both current-design expendable and low-cost reusable spacecraft, and involves spacecraft retrieval as well as delivery-only missions. Applicable mission category, spacecraft user, launch site, and number of spacecraft required by the Final Option 2 mission model are:

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Mission Category	User/Launch Site NASA WTR	NASA ETR	DOD WTR	DOD ETR	Total Spacecraft
Geostationary - Delivery	--	75	--	41	116
Retrieval	--	56	--	35	91
Midinclination - Delivery	--	6	55	--	61
Retrieval	--	4	43	--	47
Planetary - Delivery	--	25	--	--	25
Retrieval	--	--	--	--	--
Polar - Delivery	30	--	26	--	26
Retrieval	30	--	11	--	41
Totals	60	166	135	76	437

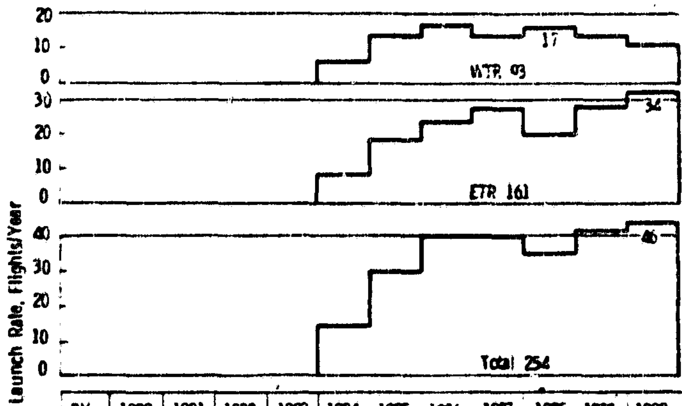
Use of the delayed retrieval flight mode (DRFM) is required for retrieval of certain geostationary spacecraft. The DRFM is required for 30 of the 56 NASA and 16 of the 35 DOD spacecraft.

By employing the multiple spacecraft delivery capability, which is within the ground rules of the mission model assessment, the 437 spacecraft can be accommodated with 293 flights (100% capture). Flight modes that make up these are:

Flight Modes	User NASA	DOD	Total Flights
Delivery	75	39	114
Kick stages	(7)	--	--
Expended Tug	(8)	--	--
Retrieval	90	89	179
Totals	165	128	293

The eight expended Tug modes and seven kick-stage modes are required to accomplish the more difficult planetary missions. All other flights are accomplished by the Tug alone, with the Tug returning to the Orbiter.

2.4.2.4.3 Programmatic Flight Summary - Figure 2.4-13 summarizes Tug flights by year and launch site for programmatic considerations. A buildup in launch rate and crew size at ETR and WTR is included; the rationale is presented in Vol 2.0, pages 2-128 through 2-131 of the *Selected Option Data Dump* (Ref 5.8). Three additional launches are included for reliability losses. This results in 254 flights for programmatic considerations compared to 293 flights required for 100% capture.



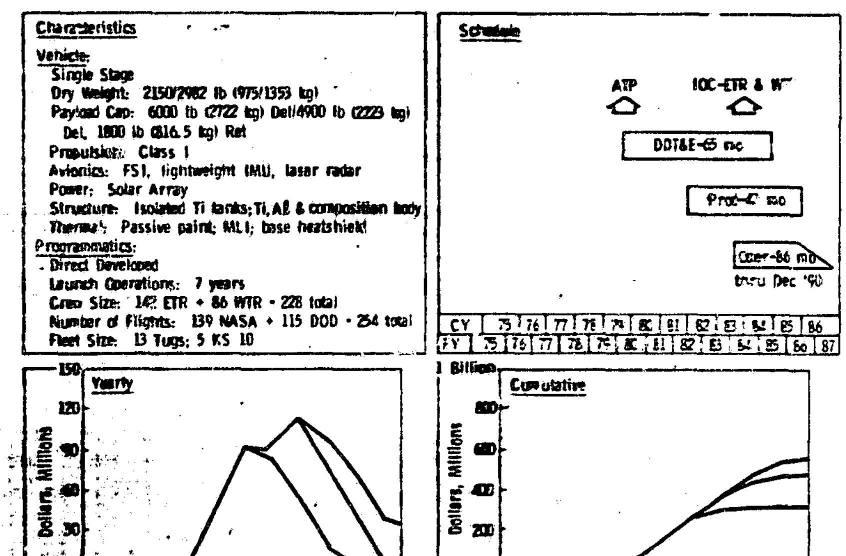
CY	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	Total
WTR					6*	13	17	14	17	14	12	93
ETR					9*	18*	25	27	20	28	34	161
Total					15*	31*	42	41	37	42	46	254

*Limited by Buildup Rate

Fig. 2.4-13 Final Option 2 Annual Flight Summary

2.4.2.5 Programmatics

2.4.2.5.1 NASA Programmatics - Programmatics data and results for Final Option 2 are summarized in Fig. 2.4-14. The program is based on completion of preliminary system and subsystem specifications during Phase B, and completion of the supporting research and technology (SRT) tasks identified for this option in paragraph 2.6 before starting DDT&E.



FY	76	77	78	79	80	81	82	83	84	85	86
DDT&E					50	94	86	52	16	1	
Prod							4	63	59	39	2
Oper									20	30	31
Total					50	94	90	115	95	70	33

FY	76	77	78	79	80	81	82	83	84	85	86	90
DDT&E					50	143	229	[illegible]	[illegible]	[illegible]	298	298
Prod							5	68	127	167	169	169
Oper									20	49	80	234
Total					50	143	234	349	444	512	547	701

Fig. 2.4-14 Final Option 2 Programmatics Summary

Because no kick stages are required before 1986, basic engineering is delayed until near completion of main-stage engineering. Production of main and kick stages is planned for concurrent completion.

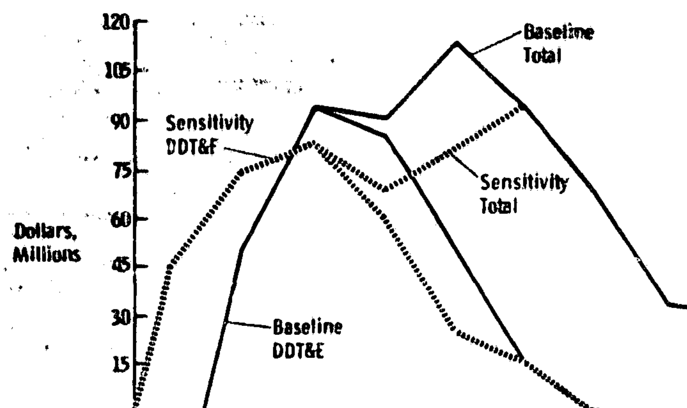
The first Tug is built during DDT&E, and the remaining 12 are built during production. Because an operational spacecraft is planned for the first launch, the operations program starts two months before first launch.

Thirteen main stages and five expendable kick stages are used for 254 flights. Six main stages are expended and three are lost due to reliability problems. Initial flight rate buildup is:

	1984	1985
ETR	9	18
WTR	6	13

The Final Option 2 Tug program schedule and associated planning discussion are in Vol 8.0, Sect. I, para 1.0, and Sect II, para 7.0 of the *Selected Option Data Dump* (Ref 5.8). Detailed program cost data are in Vol 8.0, Sect. II, and in the appendix to Vol 8.0.

2.4.2.5.2 IOC Sensitivity - A special IOC sensitivity study was conducted in which the December 1983 IOC dates for ETR and WTR were retained, but DDT&E was started one year earlier. Results are presented in Fig. 2.4-15.



Cost Summary ($ in Millions)

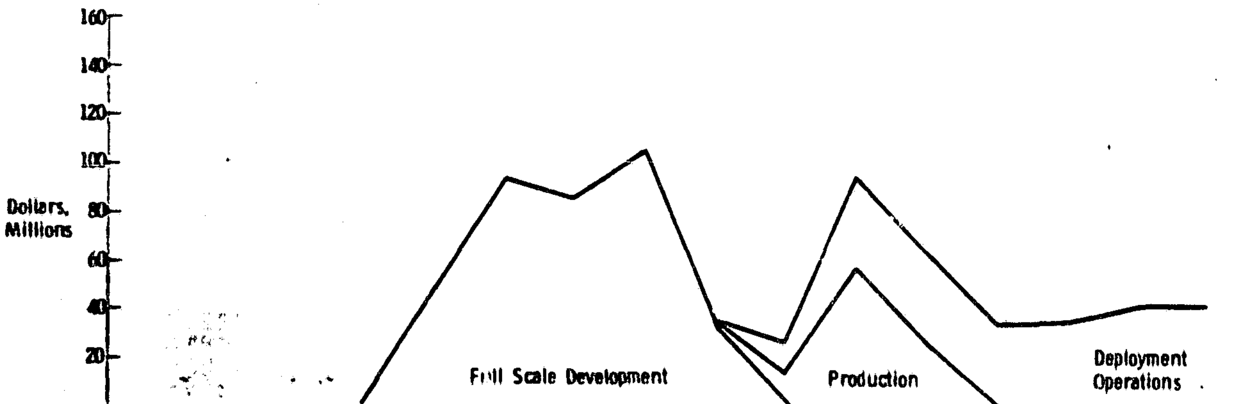
	Baseline	Sensitivity
DDT&E	297.7	305.1
Production	169.1	169.1
Operations	233.7	233.7
Total	700.5	707.9

FY	79	80	81	82	83	84	85	86	87	88	89	90	91
DDT&E													
Baseline	-0-	49.8	93.6	85.8	51.9	15.6	0.9						
Sensitivity	44.8	75.0	83.5	60.3	25.0	15.6	0.9						
Total													
Baseline	-0-	49.8	93.6	90.2	115.4	97.2	72.0	35.4	33.1	35.0	35.2	28.9	14.5
Sensitivity	44.8	75.0	83.5	69.3	83.9	97.2	72.0	35.4	33.1	35.0	35.2	28.9	14.5

Fig. 2.4-15 Final Option 2 Special Cost Sensitivity and Funding Requirements Starting DDT&E One Year Early

Starting DDT&E one year earlier reduces yearly peak funding requirements for DDT&E from $93.6 million in FY 1981 to $83.5 million; the total peak is reduced from $115.4 million in FY 1983 to $95.0 million in FY 1984. This provides a more reasonable funding distribution. Total DDT&E costs are increased by $7.5 million due to the program stretch-out.

2.4.2.5.3 <u>DOD Programmatics</u> - The major impact of DOD programmatics results from delaying the DOD production decision (DSARC III) until substantial operational test and evaluation (OT&E) data are available. This reduces potential modification requirements during production and deployment phases and provides operations experience for projecting fleet size and operations program costs. However, this delays production expenditures, resulting in uneven funding distribution, as shown in Fig. 2.4-16.



FY	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91
Dev					49.0	94.9	87.5	108.6	33.3	3.3						
Prod									3.8	10.4	59.3	26.1	0.8			
Depl										15.2	36.3	38.4	34.7	35.9	42.2	20.9
Total					49.0	94.9	87.5	108.6	37.1	28.9	95.6	64.5	35.5	35.9	42.2	20.9

Fig. 2.4-16 Final Option 2 Funding Requirements for DOD Programmatics

Assessment of DOD programmatics is summarized in paragraph 3.3. Schedule and cost data are presented in Vol 8.0, para 12.0 of the *Selected Option Data Dump*, and a comparison of DOD and NASA schedules is presented in para 1.0.

2.4.2.6 <u>Sensitivity Studies</u> - Ten sensitivities studies were directed. One was peculiar to Final Option 1 and discussed in para 2.4.1.6. The remaining nine--all presented in detail in Vol 5.0, Sect. II of the *Selected Option Data Dump* (Ref 5.8)--are based on Final Option 2 but are also generally applicable to Final Option 3. They are briefly discussed in the following pages.

a. Autonomy Levels - The purpose of this study was to evaluate the effect of different Autonomy Levels (I, II, III and IV) on vehicle design and operations. Although the vehicle is Autonomy Level II, for this study, Level IV was used as a baseline. It was determined that, unless the system was completely redesigned and optimized for Autonomy Level IV, there is no significant effect on either the vehicle or operations except for Level I, which imposes a performance penalty of 190 lb (86.2 kg) on delivery capability to geostationary orbit.

b. 0.97 Reliability - This study evaluated the design impact of maintaining 0.97 reliability for missions of 168, 72, and 36 hr. It was determined that there is no impact delta and no reliability sensitivity. Fail-operate/fail-safe requirements dictate that all redundancy provided for the 168-hr mission be retained for the two shorter missions.

c. 30-day Servicing Mission Sensitivity Study - This study was to determine subsystem impacts and resulting capability of performing a 30-day servicing mission. The mission definition was provided by the government, and the servicing mission payload considered was a servicing module (SM) and four space replaceable units (SRU), to be installed in four geostationary spacecraft.

Two servicing modes were examined: Mode 1 expended the SRUs after each satellite was serviced; Mode 2 returned the SRUs to the Orbiter so the payload up was the same as the payload down.

Assuming the SRUs were in the 140- to 500-lb (63.5 to 226.8-kg) range, it was concluded that the vehicle could perform the 30-day servicing at very little additional cost.

d. DOD Communications - The Tug provides communications for both DOD and NASA. This study was to determine the effect on Tug performance and cost if the DOD communications requirement were eliminated. It was determined that the effect would not be significant.

e. Spacecraft Command, Control, and Checkout - Through the Tug data management subsystem, command, control, and checkout capability is provided for the spacecraft. The study was to determine the effect on the Tug if this capability were not required.

Relative to the data management subsystem, the spacecraft was found to be essentially no different from any other user, and elimination of the spacecraft as a user would have no effect on Tug hardware, and very minor effect on Tug software.

f. Structural Design Life - The structural design life sensitivity study was based on analysis of only the main propellant tanks, and was performed as the last step in an orderly and logical sequence of steps in the design of these tanks. The study was to determine the effect of increasing the design life from 20 reuses to 50 and 100.

Since establishing the requirement for this study, the tanks have been redesigned using fail-leak/fail-burst criteria. The redesign was analyzed using a crack growth program to determine its life capability, which resulted in a capability of about 100 reuses. Although the analysis in this study is preliminary, it appears that there is no effect of increasing design life.

g. Spin-Stabilized Spacecraft Deployment/Retrieval - This study was to determine the effect on vehicle performance if the spacecraft spin/despin capability were removed. It was shown that its elimination provided a net delta spacecraft retrieval capability of +75 lb (+34.02 kg). Thus, the effect on vehicle performance was insignificant.

h. Rendezvous and Docking - This study evaluated the effect on vehicle performance and cost of providing rendezvous and docking capability. Basically, the study was performed by comparing the delivery-only vehicle with the retrieval vehicle. This involved documenting the differences in weight, cost, and risk between the relatively simple separation module and the more complex rendezvous and docking module. Resulting data revealed a heavy payload weight penalty [-1100 lb (-499 kg)], high costs, and relatively high development risks.

i. Engine Sensitivity Class I vs Class II - The Final Option 2 engine now used is Class I. A sensitivity analysis was performed to determine the effect on performance, cost, schedule, and technology of using a Class II engine instead. Engine performance used to compute vehicle capability for the geostationary mission is:

Engine	I_{sp}, sec	N-s/kg	Weight, lb	kg	Thrust, lb	N	MR
Class I	338	3315	268	121.6	12,000	53,379	1.90
Class II	344	3377	261	118.4	12,000	53,379	2.05

The increase in retrieval capability with the Class II engine has a significant effect on total program cost. Examination of the mission model shows that approximately 50% of the retrieved spacecraft weigh 2100 lb (952.5 kg). The Class II engine can perform these missions without resorting to delayed retrieval, as required for the Class I engine. The effect on total program cost is a reduction in Shuttle flights of approximately ten, or a total program savings of more than $100,000,000.

Although the Class II engine does not appear to be attractive from a subsystem standpoint, based on cost and performance when compared to other engine candidates, it is an attractive option when total program costs are evaluated. However, due to the risk associated with obtaining Class II performance, the Class I engine is recommended.

2.4.3 Final Option 3

2.4.3.1 Option Definition - The Final Option 3 space vehicle is a reusable phase-developed Tug, designed for a maximum mission of seven-days. The design includes growth potential from an initial delivery only capability in 1979 to a delivery/retrieval capability in 1983. Final Option 3 mission requirements include delivery only of spacecraft weighing 3500 lb (1588 kg) or less, phased to a capability of retrieving payloads weighing up to 2200 lb (998 kg).

2.4.3.2 Configuration - The space vehicle selected for Final Option 3 is a reusable single-stage vehicle, designated Final Option 3, Phased Tug-Initial (IA2-8) and Final Option 3, Phased Tug-Final Delivery (IA2-4)/Retrieval (IA2-3). It is designed for seven-day delivery-only missions in 1979 (designated Phase Tug-Initial), accompanied by kits designed to permit delivery/retrieval and delayed retrieval flight mode (DRFM) missions in 1983 (designated Phased Tug-Final). The vehicle is capable of operating within the specified environment with Autonomy Level II and at a reliability of 0.97. Geostationary orbit capabilities are:

Delivery only (IA2-8) 1979	4400 lb (1996 kg)
Delivery only (IA2-4) 1983	6000 lb (2722 kg)
Retrieval only (IA2-3) 1983	1800 lb (816.5 kg)
Retrieval only--DRFM (IA2-3) 1983	2200 lb (998 kg)

For expansion of Final Option 3 Tug performance and flight modes, refer to Vol 5.0, Sect. II of the *Selected Option Data Dump* (Ref 5.8).

On certain planetary missions, the Final Option 3 Tug is combined with one of three auxiliary kick-stage arrangements (para 2.2.11): one with 10,000 lb (4536 kg) of propellants, one with 1500 lb (680.4 kg), or a combination of the two. In all cases, kick stages are expended and the Tug returns to the Orbiter.

The 1979 delivery-only vehicle (Phased Tug-Initial) shown in Fig. 2.4-17 and 2.4-18 is 28 ft 2 in. (8.59 m) long from the forward face of the separation module (not shown in figures) to the aft end of the engine bell, with a dry weight (including 10% contingency) of 2934 lb (1331 kg).

The 1983 delivery-only vehicle (Phases Tug-Final) shown in Fig. 2.4-19 and 2.4-20, is 27 ft 4 in. (8.33 m) long from the forward face of the separation module (not shown in figures) to the aft end of the engine bell, with a dry weight (including 10% contingency) of 2750 lb (1247 kg).

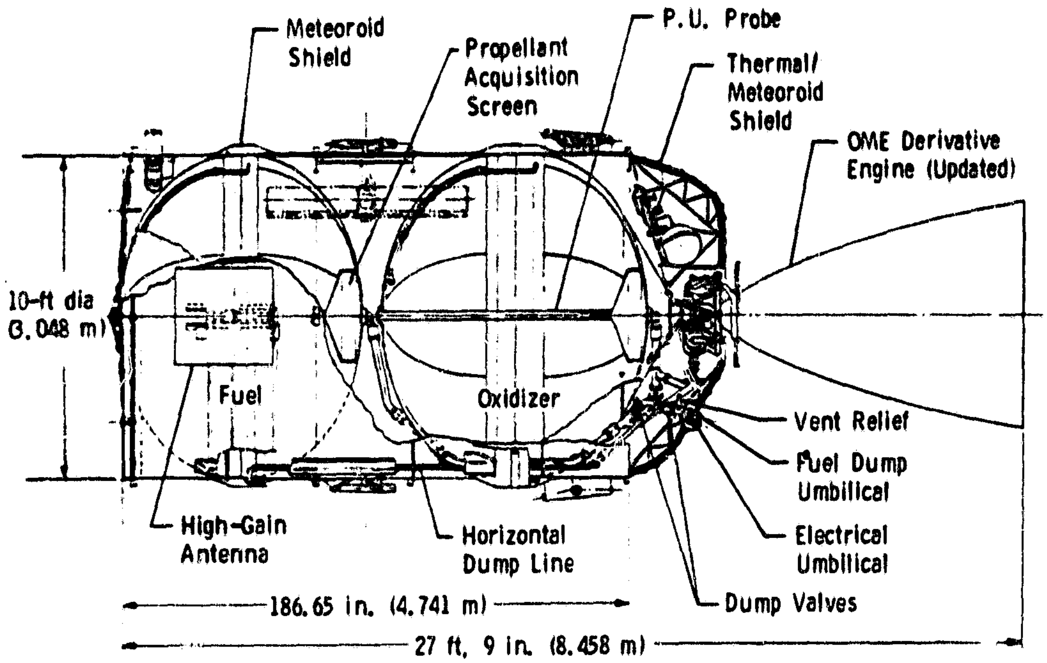


Fig. 2.4-17 Final Option 3 Phased Tug-Initial Inboard Profile

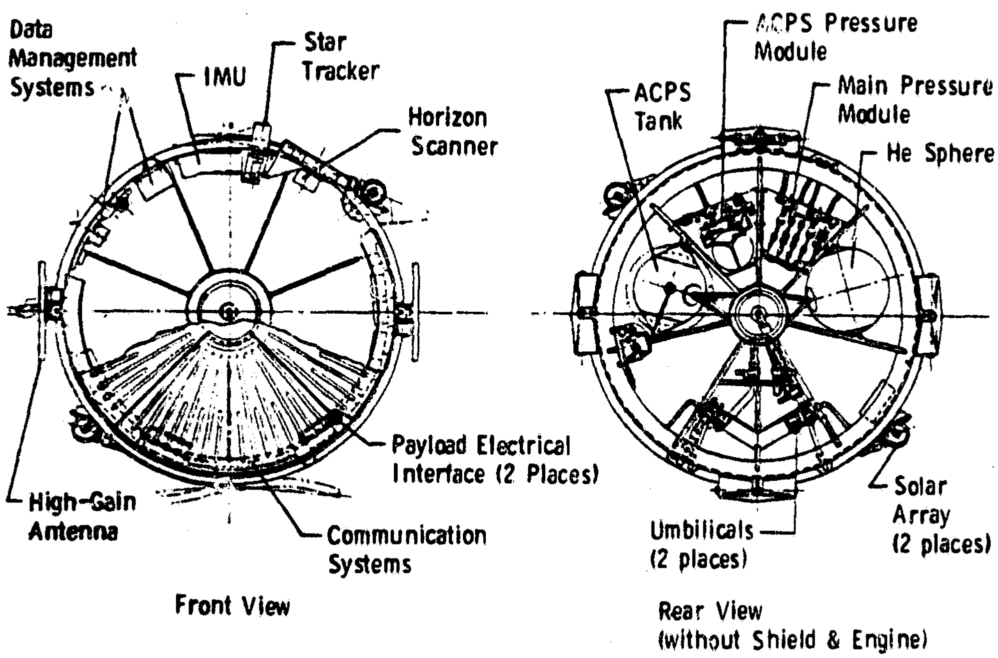


Fig. 2.4-18 Final Option 3 Phaes Tug-Initial Inboard End Views

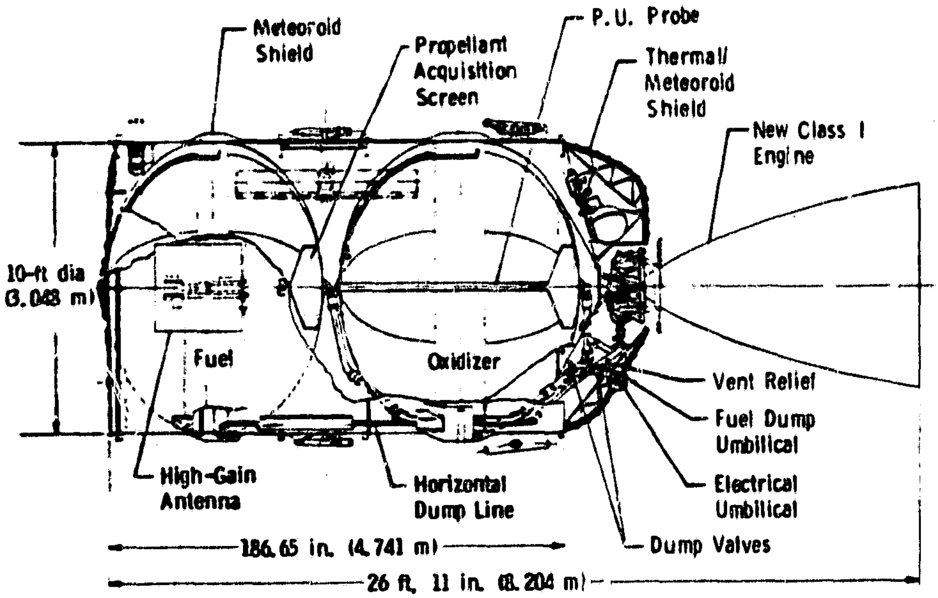


Fig. 2.4-19 Final Option 3 Phased Tug-Final Delivery/Retrieval Inboard Profile

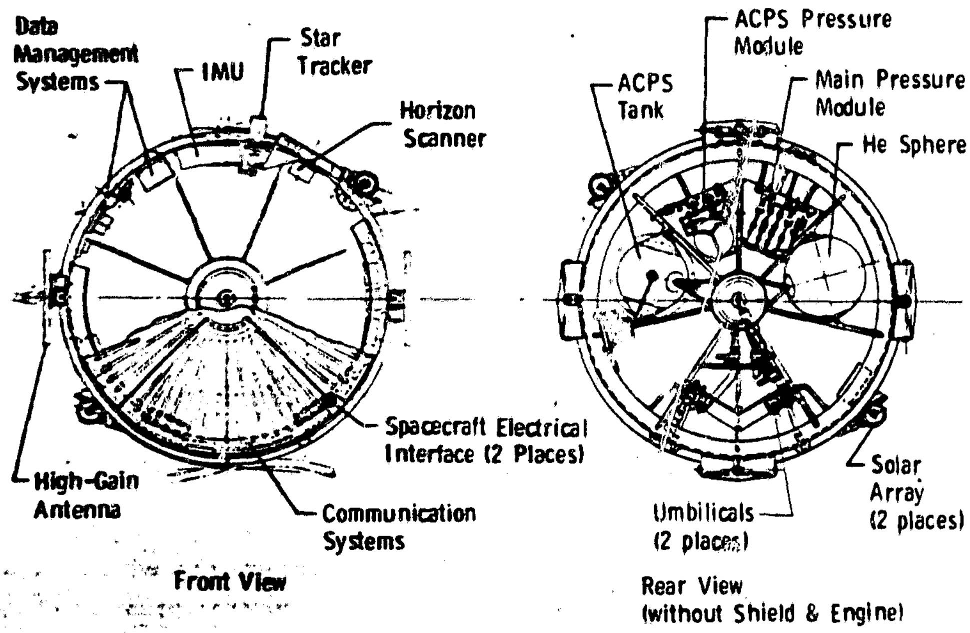


Fig. 2.4-20 Final Option 3 Phased Tug-Final Delivery/Retrieval Inboard End Views

The 1983 retrieval vehicle (Phased Tug-Final), is also shown in Fig. 2.4-19 and 2.4-20, is 28 ft 8 in. (8.74 m) long from the forward face of the docking module (not shown) to the aft end of the engine bell, with a dry weight (including 10% contingency) of 2982 lb (1353 kg).

The following paragraphs are brief descriptions of the integrated vehicle subsystems that make up the complete Final Option 3 Tug. Detailed subsystem descriptions are in para 2.2. For clarification and continuity in this document, the following descriptions refer to previously assigned subsystem designators.

2.4.3.2.1 Structure - The Tug structure primarily comprises four elements: propellant tankage, engine compartment, forward equipment compartment, and spacecraft interface. The propellant tanks are isolated, titanium tanks (fuel forward) with $\sqrt{2}$ elliptical domes, designed for 60,000 lb (27,216 kg) of total propellants at a mixture ratio of 1.9. The tanks are joined by a skirt of composite honeycomb using graphite epoxy face sheets over an aluminum honeycomb core. Radial meteoroid shielding is provided for the portion of each tank not covered by the body structure.

The engine compartment skirt is graphite epoxy over an aluminum honeycomb core. The engine thrust cone is titanium.

The forward equipment compartment skirt is aluminum skin-stringer construction. All structural ring frames, hard points, and splices are titanium.

The spacecraft interface for delivery-only (1979 and 1983) is a 10-ft (3.048-m) diameter by 5-in. (12.7-cm) deep separation module containing separation ordnance and the spacecraft deployment assembly. Paragraph 2.2.9 provides a detailed description of the module.

The spacecraft interface for retrieval is a 10-ft (3.048-m) dia by 21-in. (53.34-cm) deep docking module containing the docking mechanism, scanning laser radar unit, and video subsystem. This unit also has spacecraft delivery capability for use in the delayed retrieval mode (DRFM) for deploying a replacement spacecraft. Paragraph 2.2.10 provides a detailed description of this module.

2.4.3.2.2 Thermal Control -As in the Final Option 1 and 2 configurations, the thermal control subsystem, designated TH-5, is passive, using thermal paint and multilayer insulation. Special optical solar reflector material is used at the avionics equipment compartment; radiation shields are applied at the ACPS thrusters; and heat pipes are used between the batteries and forward tank dome. Electric heaters are used for low-temperature-critical components.

2.4.3.2.3 Data Management - The data management subsystem, common to all Tugs, uses a flexible signal interface (FSI) and consists of a central data processor, encrypter/decrypter unit (GFE), branch boxes, and interconnecting cabling. The central processor contains units required for general-purpose and command-data-timing-checkout (CDTC) processing and memory.

2.4.3.2.4 Guidance, Navigation, and Control - For the 1979 delivery-only capability, a star tracker and skewed redundant IMUs are used for guidance and navigation. In 1983, IMUs will be changed to lighter equipment. Rendezvous and docking capability is achieved by adding a scanning laser radar (SLR) and video subsystem (mounted in the docking module).

Although the Tug is baselined at Autonomy Level II, addition of a horizon sensor would permit upgrading to Autonomy Level I operation.

A pair of electrically driven, tandem linear hydraulic actuators is used for pitch and yaw control in powered flight, with roll control obtained from the ACPS thrusters. Attitude in coast flight is controlled solely by the ACPS system.

2.4.3.2.5 Communications - The all-S-band communications subsystem, common to all Tugs, consists of high-gain antennas and gimbal assemblies, a strip-line omnidirectional antenna, FM and PM transmitters, receivers, power amplifiers, a coupling and switching network and coaxial cable harness.

2.4.3.2.6 Instrumentation - The instrumentation subsystem is not separate, but is integral with the flexible signal interface (FSI) data management subsytem, with end-item instrumentation units (pressure transducers, temperature recording controllers, etc) provided by the applicable user subsystem and interfacing with the applicable FSI branch circuit.

2.4.3.2.7 Electrical Power, Distribution, and Control - The Final Option 3 Tug electrical power subsytem is a deployable solar-array/Ag-Zn battery system, consisting of redundant flexible roll-out/retractable solar-panel assemblies attached to the vehicle by panel-orientation mechanisms with two-axis freedom, redundant charger/load-regulator units, Ag-Zn 165-Ah main and 25-Ah auxiliary storage batteries, power distributors, wiring, and connectors. The distribution system uses a two-wire positive and single-wire return and has solid-state remote power controllers and relays. A compatible interface with the Orbiter is provided. Solar panels and orientation assemblies are g-limited and must be retracted during main-engine burns.

In delivery-only vehicles, ordnance squibs, detonating blocks, the squib firing circuit (SFC) and separation-module detonating cord are parts of the electrical power subsystem.

The data management; guidance, navigation, and control; communications; instrumentation; and power subsystem comprise the Final Option 3 Tug avionics system. The system for the 1979 delivery-only vehicle is designated AV-1. The designator is changed to AV-3 in the 1983 delivery-only Tug when the lighter avionics equipment is installed, and to AV-2 in the 1983 retrieval Tug when rendezvous and docking capability is added.

2.4.3.2.8 Propulsion - The propulsion system consists of the main engine and auxiliary-control propulsion subsystems.

For the delivery-only Initial Tug (1979), the main engine (GFE) is derived from OME and uprated to 240 P_c, 330-sec I_{sp} (3236-N-s/kg), 12,000 lb (53,379 N) thrust, and a mixture ratio of 1.9.

For the delivery/retrieval Final Tug (1983), the main engine is phased to a new Class I, 800 P_c engine (GFE) with 338-sec I_{sp} (3315-N-s/kg), 12,000 lb (53,379 N) thrust and a mixture ratio of 1.9. The main engine support system is the same for either main engine. The system, designated PR-1 (2B), has a regulated helium-ambient-storage propellant pressurization, feed, and dumping system that permits horizontal or vertical dumping.

The 1979 Initial Tug ACPS, designated ACPS-2(8A), consists of 16 thrusters (four modules) using a monopropellant (hydrazine) with a capability of 62,500-lb-sec (278,014-N-s) impulse, and 3700-psig (2551-N/cm^2) helium as the pressurant.

In 1983, the ACPS for the delivery-only configuration, designated ACPS-2(8C), has a capability of 62,500-lb-sec (278,014-N-s) impulse. For the rendezvous and docking capability, the system total impulse is increased to 125,000 lb-sec (556,028 N-s) by the use of a larger tank, and is designated ACPS-2(8B).

2.4.3.2.9 Reliability - Final Option 3 Tug reliabilities meet or exceed the requirement of 0.97 for all missions, with or without kick stages. A detailed description of system and subsystem reliability is in Vol 5.0 of the *Selected Option Data Dump* (Ref 5.8).

2.4.3.3 <u>Mass Properties</u> - Vehicle weights, centers of gravity, and moments of inertia are presented in detail in Vol 5.0 of Ref 5.8. In summary, the Option 3 Tug weights and the center-of-gravity travel are:

a. *Weight Summary*

	Weight, lb (kg)		
Item	1979 Delivery-Only Tug	1983 Delivery-Only Tug	1983 Retrieval Tug
Tug dry weight*	2,934 (1,331)	2,750 (1,247)	2,983 (1,353)
Structure	1,063 (482.2)	1,063 (482.2)	1,176 (533.4)
Thermal control	101 (45.8)	101 (45.8)	101 (45.8)
Avionics	640 (290.3)	593 (269)	669 (303.4)
Propulsion	863 (391.5)	743 (337)	765 (347)
Unusable Propellants	225 (102)	220 (99.8)	251 (113.8)
Burn-out weight	3,159 (1,433)	2,970 (1,347)	3,233 (1,466)
Nonimpulsive expendables	75 (34.02)	50 (22.7)	50 (22.7)
Propellants (usable)	60,019 (27,224)	60,049 (27,238)	60,319 (27,360)
First-ignition weight	63,253 (28,691)	63,069 (28,608)	63,602 (28,849)
Shuttle interface	1,650 (748.4)	1,650 (748.4)	1,650 (748.4)
Tug mass fraction	0.950	0.953	0.949

*Includes 10% contingency.

b. *Center-of-Gravity Travel* - Center-of-gravity travel with a typical 3500-lb (1588-kg) 25-ft (7.62-m) spacecraft attached remains well within the allowable Shuttle payload cg envelope. The longitudinal and vertical centers of gravity versus allowable envelope are shown in Fig. 2.4-3 and -4. respectively. The lateral cg falls within 3/4 in. (1.91 cm) of the Shuttle payload-bay centerline.

2.4.3.4 Mission Accomplishments - As used in this report, mission accomplishments cover performance, capture summary, and annual flight summary--all with respect to the mission model.

2.4.3.4.1 Performance - Performance capabilities of the Final Option 3 delivery-only and delivery/retrieval Tugs are shown in Fig. 2.4-21, with spacecraft weight versus delta velocity. Performance to various orbital inclinations is shown, as well as performance for the various modes previously discussed. Circles on the plot represent characteristics of the mission model spacecraft. The heavy concentration of points at the 14,000 fps (4267 m/s) velocity represents the geostationary corridor.

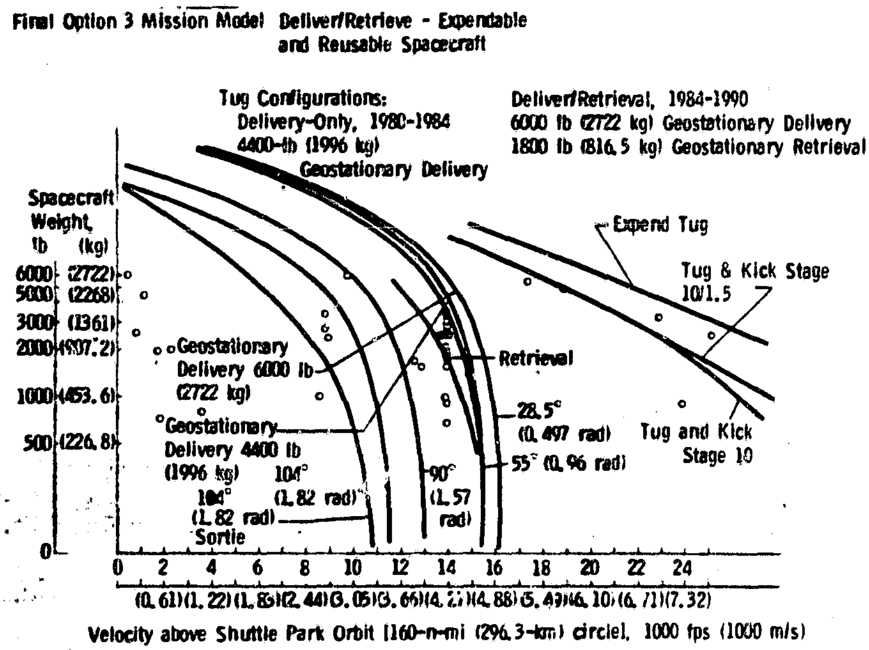


Fig. 2.4-21 Final Option 3 Mission Model and Tug Performance

2.4.3.4.2 100% Capture Summary - A total of 558 spacecraft must be accommodated by the Final Option 3 mission model described in Vol 4.0 of the *Selected Option Data Dump* (Ref 5.8). Final Option 3 consists of both current-design expendable and low-cost reusable spacecraft, and requires spacecraft retrieval as well as delivery-only missions. Applicable mission category, spacecraft user, launch site, and number of spacecraft required by the Final Option 3 mission model are:

Mission Category	User/Launch Site/Spacecraft NASA WTR	NASA ETR	DOD WTR	DOD ETR	Total Spacecraft
Geostationary - Delivery	--	123	--	59	182
- Retrieval	--	53	--	29	82
Midinclination - Delivery	--	10	27	66	103
- Retrieval	--	4	--	43	47
Planetary - Delivery	--	30	--	--	--
- Retrieval	--	--	--	--	--
Polar - Delivery	38	--	34	--	72
- Retrieval	30	--	12	--	42
Totals	68	220	73	197	558

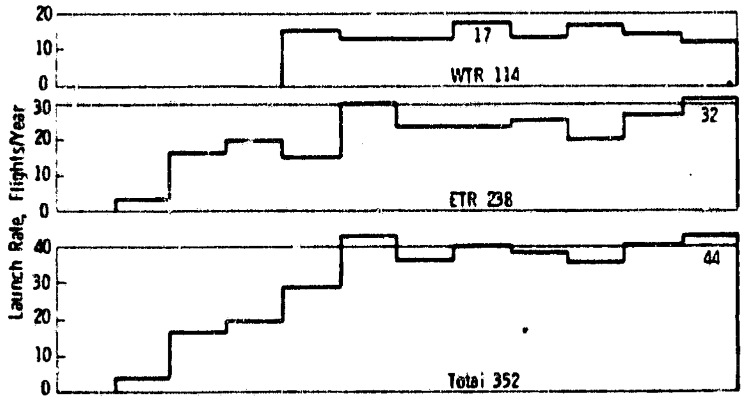
Use of the delayed retrieval flight mode (DRFM) is required for retrieval of certain geostationary spacecraft. The DRFM is required for 27 of the 53 NASA and 10 of the 29 DOD spacecraft.

By employing the multiple spacecraft delivery capability, which is within the ground rules of the mission model assessment, the 558 spacecraft can be accommodated with 366 flights (100% capture). Flight modes that make up these are:

Flight Modes	User NASA	User DOD	Total Flights
Delivery	115	80	195
Kick stages	(9)	--	--
Expended Tugs	(8)	--	--
Retrieval	87	84	171
Totals	202	164	366

The eight expended Tug modes and nine kick-stage modes are required to accomplish the more difficult planetary missions. All other flights are accomplished by the Tug alone, with the Tug returning to the Orbiter.

2.4.3.4.3 Programmatic Flight Summary - Figure 2.4-22 summarizes Tug flights by year and launch site for programmatic considerations. The number of flights in the first year is limited to three by Shuttle availability. Four additional launches are included for reliability losses. This results in 352 flights, for programmatic consideration compared to 366 flights required for 100% capture.



CY	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	Total
WTR	0	0	0	14	13	14	17	14	16	14	12	114
ETR	3*	17	20	15	30	24	24	26	20	27	32	238
Total	3*	17	20	29	43	36	41	40	36	41	44	352

*Limited by Shuttle Availability

Fig. 2.4-22 Final Option 3 Annual Flight Summary

2.4.3.5 Programmatics

2.4.3.5.1 NASA Programmatics - NASA programmatics data and results for Final Option 3 are summarized in Fig. 2.4-23. The program is based on completion of preliminary system and subsystem specifications during Phase B, completion of supporting research and technology (SRT) tasks identified for Final Option 3 1979 IOC (Phased Tug-Initial) in para 2.6 before starting DDT&E, and completing the Final Option 3, 1983 IOC (Phased Tug-Final) SRT tasks by October 1, 1978.

Because no kick stages are required before 1982, basic engineering is delayed until near completion of main-stage engineering for the Phased Tug-Initial configuration.

The first Tug is built during DDT&E, and the remaining 15 are built during production. Production completion is controlled by delivery of the last Tug. Phased Tug-Final configuration changes will be developed in DDT&E and all delivered hardware will be built during production. Because an operational spacecraft is planned for the first launch, the operations program starts two months before first launch.

Sixteen main stages and nine expendable kick stages are used for 352 flights. Eight main stages are expended and four are lost due to reliability problems. Shuttle availability limits the number of flights in 1980 to three.

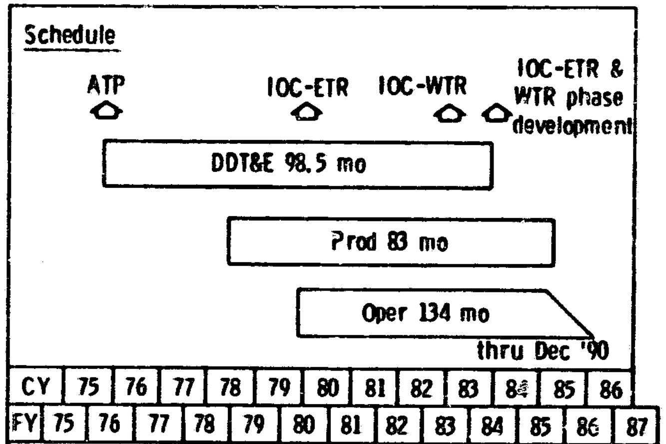
Characteristics

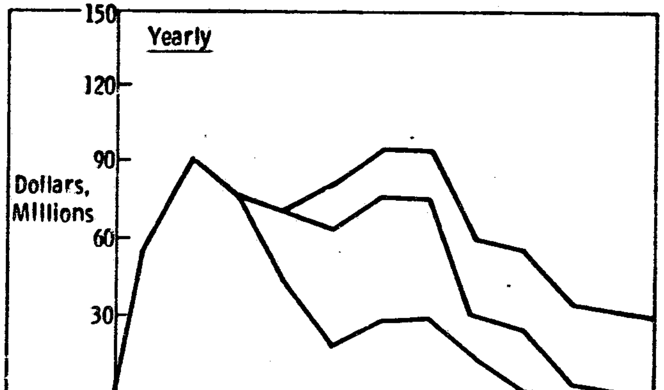
Vehicle:

Single Stage
Dry Weight: 2934 lb → 2750/2982 lb (1331 → 1247/1353 kg)
Spacecraft Cap: 4400 lb (1996 kg) del → 6000 lb (2722kg) del/4900 lb (2223 kg)
Propulsion: High P_c OME → Class I del, 1800 lb (816.5 kg) retrieval
Avionics: FSI; current IMU → Lightweight IMU, SLR
Power: Solar array
Structure: Isolated Ti tanks; Ti, Aℓ & composite body
Thermal: Passive paint, MLI; base heatshield

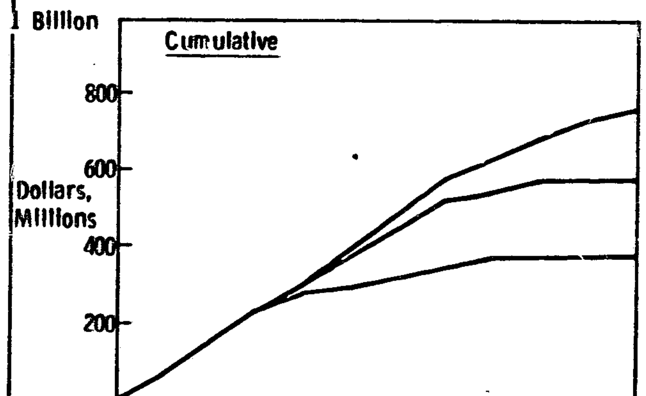
Programmatics:

Phase Developed
Launch Operations: 11 years
Crew Size: 142 ETR + 86 WTR = 228 total
Number of Flights: 196 NASA + 156 DOD = 352 total
Fleet Size: 16 Tugs; 5 KS 10; 4 KS 10/1.5





FY	76	77	78	79	80	81	82	83	84	85	86
DDT&E	55	91	76	44	18	28	30	12	1		
PROD				26	46	49	43	18	23	4	
OPER					16	19	22	29	31	31	31
TOTAL	55	91	76	70	80	96	95	59	55	35	31

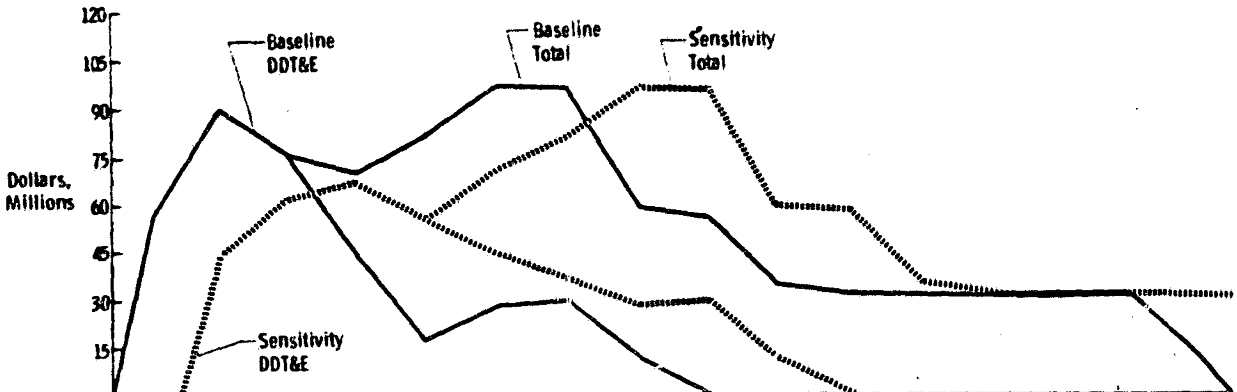


FY	76	77	78	79	80	81	82	83	84	85	86	90
DDT&E	55	146	222	266	284	312	341	353	353	354	354	354
PROD				26	71	120	164	182	206	209	209	209
OPER					16	35	57	86	117	148	178	318
TOTAL	55	146	222	292	371	467	562	621	676	711	741	881

Fig. 2.4-23 Final Option 3 Programmatics Summary

The Final Option 3 Tug program schedule and associated planning discussion are in Vol 8.0, Sect. I, para 1.0, and Sect. II, para 7.0 of the *Selected Option Data Dump* (Ref 5.8). Detailed program cost data are in Vol 8.0, Sect. II and the appendix to Vol 8.0.

2.4.3.5.2 IOC Sensitivity - An IOC sensitivity study was conducted in which IOC dates for ETR and WTR were delayed two years. Results are presented in Fig. 2.4-24.



	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91
DDT&E																
Baseline	54.7	90.8	76.1	44.3	18.1	27.9	29.5	11.8	0.6							
Sensitivity		44.0	62.0	68.0	55.0	44.3	18.1	27.9	29.5	11.8	0.6					
Total																
Baseline	54.7	90.8	76.1	70.3	79.7	95.7	95.2	58.8	55.1	34.8	31.1	31.3	31.2	31.1	31.3	14.6
Sensitivity		44.0	62.0	68.0	55.0	70.3	79.7	95.7	95.2	58.8	58.1	34.8	31.1	31.3	31.2	31.1

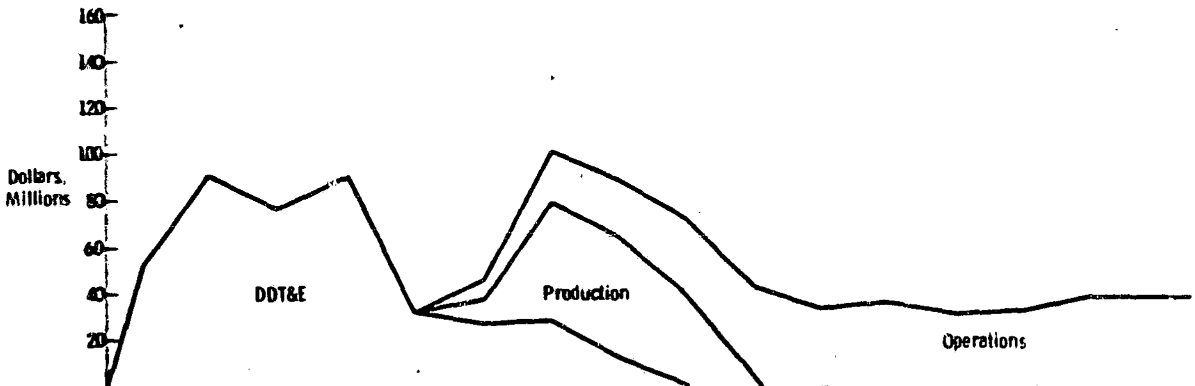
Fig. 2.4-24 Final Option 3 Cost Sensitivity and Funding Requirements for Dec 1981 IOC

Delaying IOC two years reduces yearly peak funding requirements for DDT&E from $90.8 million in FY 1977 to $68.0 million in FY 1979, providing a more reasonable funding distribution. However, the IOC for the Phased Tug-Final is delayed two years, which appears to be unnecessary. Total DDT&E costs are increased by $7.4 million due to the program stretch-out.

Additional details are presented in Vol 8.0, Sect. II, para 8.0 of the *Selected Option Data Dump* (Ref 5.8).

Additional IOC studies were conducted on Final Option 3 after the September data dump. Results are summarized in para 3.4 and 3.5.

2.4.3.5.3 DOD Programmatics - The major impact of DOD programmatics results from delaying the DOD production decision (DSARC III) until substantial operational test and evaluation (OT&E) data are available. This reduces potential modification requirements during production and deployment phases and provides operations experience for projecting fleet size and operations program costs. However, this delays production expenditures, resulting in uneven funding distribution, as shown in Fig. 2.4-25.



FY	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91
Dev	53.8	90.5	78.5	85.0	30.3	28.6	28.8	11.6	0.7							
Prod						10.0	50.2	51.4	40.2	6.1						
Depl						7.2	21.7	21.5	31.6	37.0	33.9	37.0	31.6	34.3	39.3	20.6
Total	53.8	90.5	78.5	85.0	30.3	45.8	100.7	84.5	72.5	43.1	33.9	37.0	31.6	34.3	39.3	20.6

Fig. 2.4-25 Final Option 3 Funding Requirements for DOD Programmatics

Assessment of DOD programmatics is summarized in para 3.3. Schedule and cost data are presented in Vol 8.0, para 12.0 of the *Selected Option Data Dump* (Ref 5.8); a comparison of DOD and NASA schedules is presented in para 1.8.

2.4.3.6 Sensitivity Studies - In addition to the sensitivity studies discussed in para 2.4.2.6, one additional study was performed for Final Option 3:

Engine Sensitivity to Not Phasing Engines - For Final Option 3, the main engine is now shown phased from a 240-P_c OME to Class I. A sensitivity analysis was performed to determine the cost savings to the Tug program of not phasing the engines. Engine performance used to compute vehicle capability for the geostationary mission in 1983 is:

Engine	I_{sp}, sec (N-sec/kg)	Weight, lb (kg)	Thrust, lb (N)	MR	Delivery, lb (kg)	Retrieval, lb (kg)
OME 240	330.3 (3239)	398 (180.5)	12,000 (53,379)	1.90	4690 (2127)	1280 (580.6)
Class I	338.0 (3315)	268 (121.6)	12,000 (53,379)	1.90	6000 (2722)	1800 (816.5)
8096B-2	332.1 (3257)	290 (131.5)	12,187 (53,760)	1.78	5410 (2454)	1550 (703.1)

From a schedule standpoint, all three engines could be available in December 1979, and there are no significant differences in technology requirements. The cost saving is significant and varies from $42 to $78 million. For this reason, phasing the engine is not recommended.

Further analysis was performed after the selected option data dump, taking capture analysis and total programmatics into consideration. Based on this study, the Class I engine was selected. Details are in para 3.0, Additional Analysis.

2.4.4 Final Option 3A

2.4.4.1 Option Definition - Final Option 3A space-vehicle definition and mission requirements are the same as those for Final Option 3: a reusable-phase developed Tug, tesigned for a maximum mission duration of 7 days, with built-in growth for an initial 1979 delivery-only capability of expendable spacecraft weighing 3500 lb (1588 kg) or less phased to a capability of retrieving spacecraft weighing up to 2200 lb (998 kg).

2.4.4.2 Configuration - The Final Option 3A Tug shown in Fig. 2.4-26 and -27, is a reusable one-and-a-half stage vehicle that uses expendable drop tanks, designated Final Option 3A Phased Tug-Initial (IVG-1) and Final Option 3A, Phased Tug-Final-Delivery (IV G-3)/Retrieval (IVG-2). The configurations are designed for a 7-day mission, with both spacecraft delivery and rendezvous and docking capability. The basic vehicle is phased developed from an initial delivery-only capability in 1979 (designated Phased Tug-Initial) to a delivery/retrieval and delayed retrieval flight mode (DRFM) capability in 1983 (designated Phased Tug-Final). This Tug is capable of operating in the specified environment at Autonomy Level II and a reliability of 0.97. Vehicle geostationary orbit capabilities are:

Delivery only (IVG-1) 1979	4900 lb (2223 kg)
Delivery only (IVG-3) 1983	6500 lb (2948 kg)
Retrieval only (IVG-2) 1983	1900 lb (862 kg)
Retrieval only-DRFM (IVG-2) 1983	2200 lb (998 kg)

For expansion of Final Option 3A Tug performance and flight modes, refer to Vol 5.0 of the *Selected Option Data Dump* (Ref 5.8).

On certain planetary missions, the Final Option 3A Tug is combined with one of three auxiliary kick-stage arrangements (para 2.2.11): one with 10,000 lb (4536 kg) of propellants, one with 1500 lb (680.4 kg), or a combination of the two. In all cases, kick stages are expended and the Tug returns to the Orbiter.

The 1979 delivery-only vehicle (Phased Tug-Initial) is 23 ft 4 in. (7.11 m) from the forward face of the separation module (not shown in figures) to the aft end of the engine bell, and has a dry weight (including 10% contingency) of 2616 lb (1187 kg) for the core and 1388 lb (630 kg) for the drop stage.

The 1983 delivery-only vehicle (Phased Tug-Final) is 22 ft 6 in. (6.86 m) from the forward face of the separation module (not shown in figures) to the aft end of the engine bell, and has a dry weight (including 10% contingency) of 2432 lb (1103 kg) for the core and 1388 lb (630 kg) for the drop stage.

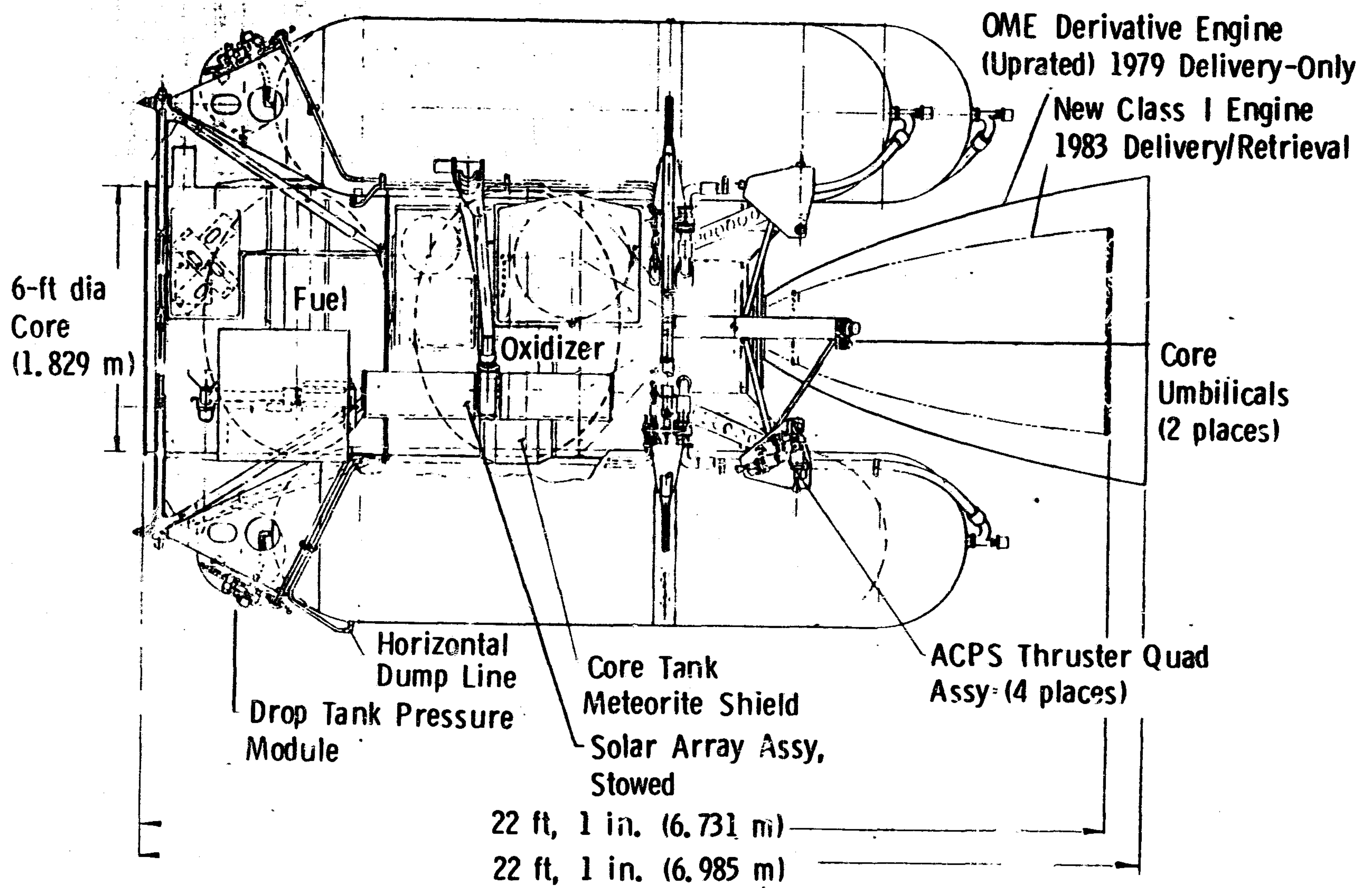


Fig. 2.4-26 Final Option 3A Phased Tug Inboard Profile

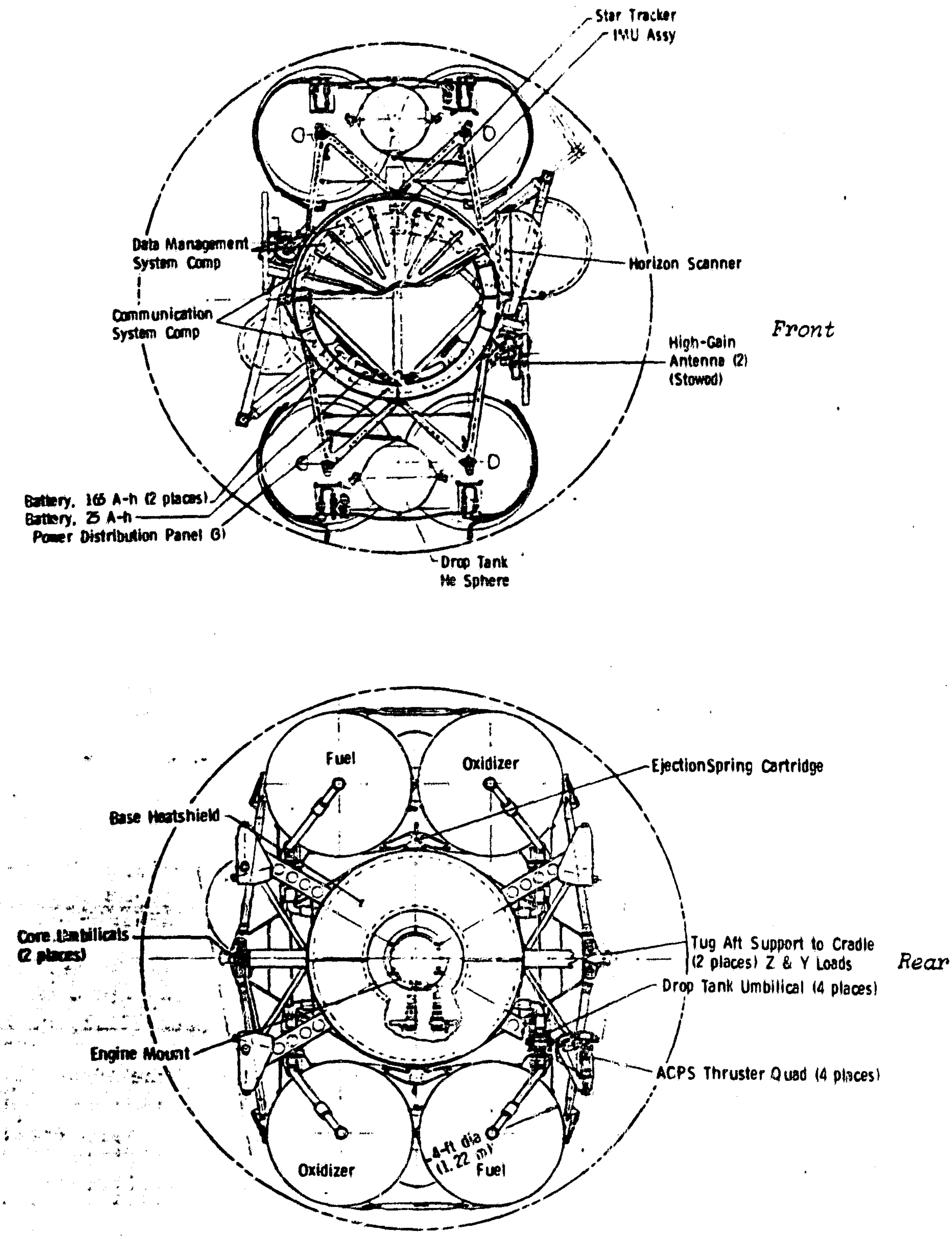


Fig. 2.4-27 Final Option 3A Phased Tug Inboard End Views

The 1983 retrieval vehicle (Phased Tug-Final) is 23 ft 10 in. (7.26 m) from the forward face of the docking mechanism (not shown in figures) to the aft end of the engine bell, and has a dry weight (including 10% contingency) of 2655 lb (1204 kg) for the core and 1388 lb (630 kg) for the drop stage.

The following paragraphs are brief descriptions of the integrated vehicle subsystems that make up the complete Final Option 3A Tug. Detailed subsystem descriptions are in para 2.2. For clarification and continuity in this document, the following descriptions refer to previously assigned subsystem designators.

2.4.4.2.1 Structure - The Tug structure primarily comprises five elements: core propellant tankage, drop tanks, engine compartment, forward equipment compartment, and spacecraft interface.

The core propellant tanks are isolated, titanium tanks (fuel forward) with $\sqrt{2}$ elliptical domes, designed for 12,000 lb (5443 kg) of propellants.

The drop tanks are two pairs of side-by-side isolated aluminum tanks with hemispherical domes and thrust cones, designed for 48,000 lb (21,772 kg) of total propellants. The propellant mixture ratio is 1.9.

The forward skirt, engine compartment, and between-tank skirts are aluminum skin-stringer construction; the thrust structure is an aluminum cone.

All structural ring frames, hard points, struts, and splices are aluminum.

The drop-tank separation mechanism consists of four forward separation-nut and spring-cartridge assemblies, four aft-tank strut separation nuts, and two aft inboard shear-key and ejection-spring-cartridge assemblies.

The spacecraft interface for delivery-only capability (1979 and 1983) is a 6-ft (1.829-m) dia by 5-in. (12.7-cm) deep separation module containing separation ordnance and the spacecraft deployment assembly Paragraph 2.2.9 provides a detailed description of the separation module.

The spacecraft interface for retrieval is a 6-ft (1.829-m) dia by 21-in. (53.34-cm) deep rendezvous and docking module containing the docking mechanism, scanning laser radar unit, and video subsystem. The unit also has spacecraft deployment capability for use in the delayed retrieval flight mode (DRFM) for deploying a replacement spacecraft. Paragraph 2.2.10 provides a detailed description of this docking module.

Radial meteoroid shielding is provided for the portion of each core propellant tank not protected by body structure and for the core helium hydrazine spheres. There is no shielding for the drop tanks or drop-tank pressure spheres.

2.4.4.2.2 Thermal Control - The thermal control subsystem, designated TH-2(1), is passive, using thermal paint on both core structure and drop tanks and multilayer insulation fore and aft on the core only. Special optical solar-reflector material is used at the avionics equipment compartment; radiation shields are applied at the ACPS thrusters; and heat pipes are used between the batteries and forward tank dome. Electrical heaters are used for low-temperature-critical components.

2.4.4.2.3 Data Management - The data management subsystem, common to all Tugs, uses a flexible signal interface (FSI) and consists of a central data processor, encrypter/decrypter unit (GFE), branch boxes, and interconnecting cabling. The central processor contains units required for general-purpose and command-data-timing checkout (CDTC) processing and memory.

2.4.4.2.4 Guidance, Navigation, and Control - For the 1979 delivery-only capability, a star tracker and skewed redundant IMUs are used for guidance and navigation. In 1983, IMUs will be changed to lighter equipment. Rendezvous and docking capability is achieved by addition of a scanning laser radar (SLR) and video subsystem (mounted in the spacecraft interface rendezvous and docking module).

Although the Tug is baselined at Autonomy Level II, addition of a horizon sensor would permit upgrading to Autonomy Level I Operation.

A pair of electrically driven, tandem linear hydraulic actuators are used for pitch and yaw control in powered flight, with roll control obtained from the ACPS thrusters. Attitude in coast flight is controlled solely by the ACPS system.

2.4.4.2.5 Communications - The all-S-Band communications subsystem, common to all Tugs, consists of high-gain antennas and gimbal assemblies, a strip-line omnidirectional antenna, FM and PM transmitters, receivers, power amplifiers, a coupling and switching network and coaxial cable harness.

2.4.4.2.6 Instrumentation - The instrumentation subsystem is not separate, but is integral with the FSI data management subsystem, with the end-item instrumentation units (pressure transducers, temperature recording controllers, etc) provided by the applicable user subsystem and interfacing with the applicable FSI branch circuit.

2.4.4.2.7 Electrical Power, Distribution, and Control - The Final Option 3A Tug electrical power subsystem is a deployable solar-array/Ag-Zn battery system consisting of redundant flexible roll-out/retractable solar-panel assemblies attached to the vehicle by panel-orientation mechanisms with two-axis freedom, redundant charger/load regulator units, Ag-Zn 165-A-h main and 25-A-h auxiliary storage batteries, power distributors, wiring, and connectors. The distribution system uses a two-wire positive and single-wire return and has solid-state remote power controllers and relays. Solar panels and orientation assemblies are g-limited and must be retracted during main-engine burns.

In the delivery-only vehicles, spacecraft separation ordnance squibs, detonating blocks, squib firing circuit (SFC) and separation-module detonating cord are parts of the electrical power system, as are the ordnance and ordnance circuitry for drop-tank separation in all configurations.

The data management; guidance, navigation, and control; communications, instrumentation; and power subsystems comprise the Final Option 3A Tug avionics system. The system for the 1979 delivery-only vehicle is designated AV-1. The designator is changed to AV-3 in the 1983 delivery-only Tug when lighter avionics equipment is installed, and to AV-2 in the 1983 retrieval Tug when the rendezvous and docking capability is added.

2.4.4.2.8 Propulsion - The propulsion subsystem consists of the main engine and auxiliary control propulsion subsystems (ACPS).

For the 1979 delivery-only Tug, the main engine (GFE) is derived from OME and uprated to 240 P_c, 330 sec I_{sp} (3236 kg), 12,000-lb (53,379-N) thrust, and a mixture ratio of 1.9.

For the 1983 delivery/retrieval Tug, the main engine is phased to a new Class I, 800-P_c engine (GFE) with 338 sec I_{sp} (3315 N-sec/kg), 12,000-lb (53,379-N) thrust, and a mixture ratio of 1.9.

The main engine support system is the same for either main engine. The system, designated PR-1 (5A), uses a regulated helium-ambient-storage propellant pressurization, feed, and dumping system that permits horizontal or vertical dumping.

The core and drop tanks have independent pressurant systems and an interconnecting propellant fill, feed, and dump system with QD and umbilical disconnects. At drop-tank separation, the umbilicals are pyrotechnically actuated.

The 1979 ACPS, designated ACPS-2 (8A), consists of 16 thrusters (four modules) using a monopropellant (hydrazine) with a capability of 62,500 lb-sec (278,014 N-sec) impulse, using 3700-psig (2551-N/cm^2) helium as the pressurant.

In 1983, the ACPS for the delivery-only vehicle, designated ACPS-2 (8C), has a capability of 62,500 lb-sec (278,014 N-sec) impulse. For the retrieval vehicle, the system has more on-board hydrazine, provides a capability of 125,000-lb-sec (556,028-N-sec) impulse, and is designated ACPS-2 (8B).

2.4.4.2.9 Reliability - Final Option 3A Tug reliabilities meet or exceed the requirement of 0.97 for all missions, with or without kick stages. A detailed description of system and subsystem reliability is in Vol 5.0 of the *Selected Option Data Dump* (Ref. 5.8).

2.4.4.3.3 Mass Properties - Vehicle weights, centers of gravity, and moments of inertia are presented in detail in Vol 5.0 (referenced above). In summary, the Final Option 3A Tug weights and cg travel are:

a. *Weight Summary*

Item	Tug Weight, lb (kg)					
	1979 Delivery-Only		1983 Delivery-Only		1983 Retrieval	
	Core	Drop Tank	Core	Drop Tank	Core	Drop Tank
Tug dry weight*	2,616 (1,187)	1,388 (630)	2,432 (1,103)	1,388 (630)	2,655 (1,204)	1,388 (630)
Structure	849 (385)	879(399)	849 (385)	879(399)	954 (433)	879(399)
Thermal control	86 (39)	0	86 (39)	0	86 (39)	0
Avionics	640 (290)	40(18.1)	593 (269)	40(18.1)	669 (303)	40(18.1)
Propulsion	803 (364)	343(156)	683 (310)	343(156)	705 (320)	343(156)
Unusable propellants	94 (42.6)	153 (69.4)	89 (40.4)	153 (69.4)	119 (54)	153 (69.4)
Burn-out weight	2,710 (1,229)	1,541 (699)	2,521 (1,143)	1,541 (699)	2,774 (1,258)	1,541 (699)
Nonimpulsive expendables	30 (13.6)	45 (20.4)	20 (9.1)	45 (20.4)	20 (9.1)	45 (20.4)
Propellants (usable)	12,182 (5,525)	47,820 (21,691)	12,197 (5,532)	47,820 (21,691)	12,467 (5,655)	47,820 (21,691)
First-ignition weight	14,922 (6,769)	49,406 (22,410)	14,738 (6,685)	49,406 (22,410)	15,201 (6,922)	49,406 (22,410)
Combined first-ignition weight	64,328 (29,179)		64,144 (29,095)		64,667 (29,332)	
Shuttle interface	1,850 (839)		1,850 (839)		1,850 (839)	
Tug mass fraction	0.818	0.969	0.829		0.818	0.969
Combined mass fraction	0.934				0.934	
*Includes 10% contingency						

b. *Center-of-Gravity Travel* - Center-of-gravity travel with a typical 3500-lb (1588-kg) 25-ft (7.62-m) spacecraft attached, remains well within the allowable Shuttle payload cg envelope. The longitudinal and vertical center of gravity versus allowable envelope are shown in Fig. 2.4-3 and -4, respectively. The lateral cg falls within 3/4 in. (1.91 cm) of the Shuttle payload-bay centerline.

2.4.4.4 Mission Accomplishments - As used in this report, mission accomplishments cover performance, capture summary, and annual flight summary--all with respect to the mission model.

2.4.4.4.1 Performance - Performance capabilities of the Final Option 3A delivery-only and delivery/retrieval Tugs are shown in Fig. 2.4-28, with spacecraft weight plotted versus delta velocity. Performance to various orbital inclinations is shown, as well as performance for the various modes previously discussed. Circles on the plot represent characteristics of the mission model spacecraft. The heavy concentration of points at the 14,000-fps (4267-m/sec) velocity represents the geostationary corridor.

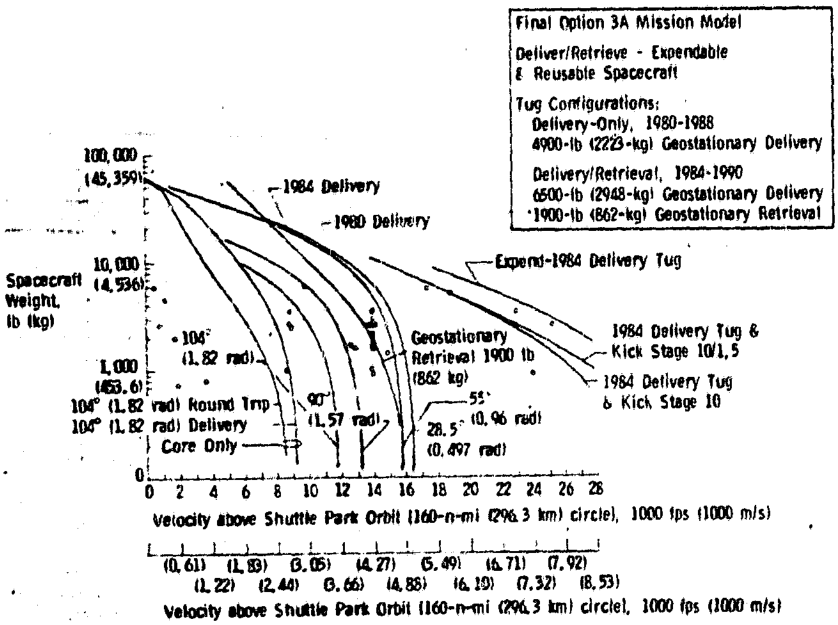


Fig. 2.4-28 Final Option 3A Mission Model and Tug Performance

2.4.4.4.2 100% Capture Summary - A total of 558 spacecraft must be accommodated by the Final Option 3A mission model described (Vol 4.0 of the *Selected Option Data Dump* (Ref 5.8). Final Option 3A consists of both current-design expendable and low-cost reusable spacecraft, and requires spacecraft retrieval as well as delivery-only missions. Applicable mission cateogry, spacecraft user, launch site, and number of spacecraft required by the Final Option 3A mission model are:

C-3

Mission Category	User/Launch Site NASA WTR	NASA ETR	DOD WTR	DOD ETR	Total Spacecraft
Geostationary - Delivery	--	123	--	59	182
- Retrieval	--	53	--	29	82
Midinclination - Delivery	--	10	--	93	103
- Retrieval	--	4	--	43	47
Planetary - Delivery	--	30	--	--	30
- Retrieval	--	--	--	--	--
Polar - Delivery	38	--	34	--	72
- Retrieval	30	--	12	--	42
Totals	68	220	46	224	558

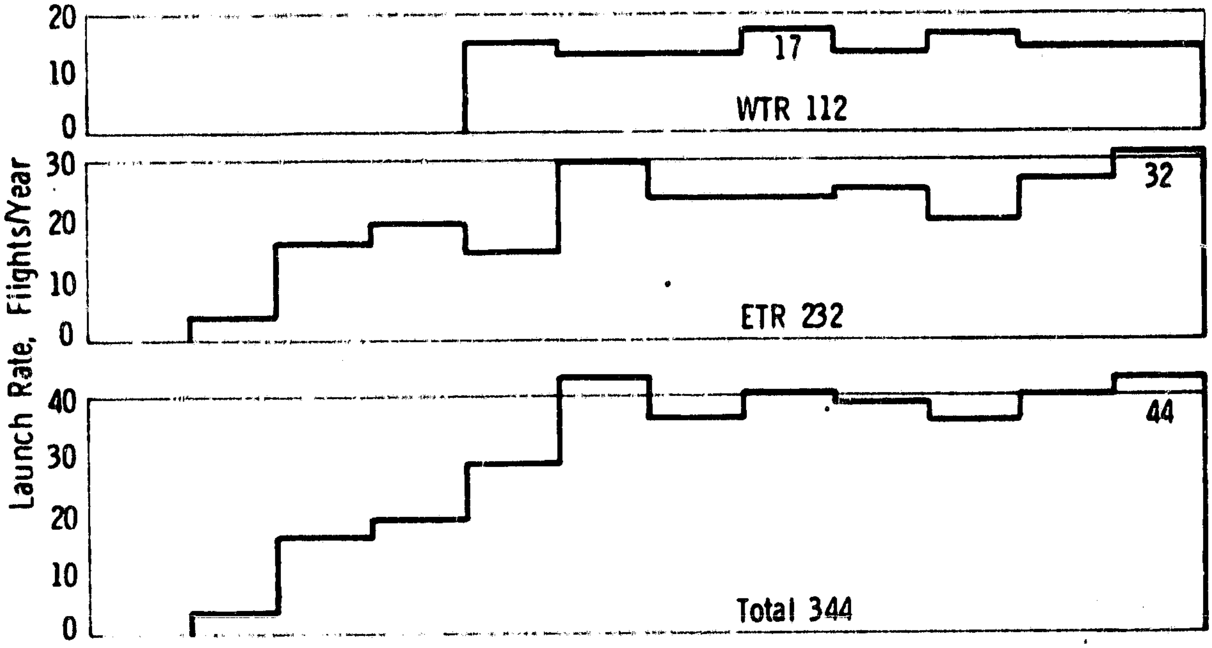
Use of the delayed retrieval flight mode (DRFM) is required for retrieval of certain geostationary spacecraft. The DRFM is required for 27 of the 53 NASA and 10 of the 29 DOD spacecraft.

By employing the multiple spacecraft delivery capability, which is within the ground rules of the mission model assessment, the 558 spacecraft can be accommodated with 357 flights (100% capture). Flight modes that make up these 357 flights are:

Flight Modes	User NASA	User DOD	Total Flights
Delivery	107	79	186
Kick stages	(9)	--	--
Expended Tugs	(8)	--	--
Retrieval	87	84	171
Totals	194	163	357

The eight expended Tug modes and nine kick-stage modes are required to accomplish the more difficult planetary missions. All other flights are accomplished by the Tug alone, with the Tug returning to the Orbiter.

2.4.4.4.3 Programmatic Flight Summary - Figure 2.4-29 summarizes Tug flights by year and launch site for programmatic considerations. The number of flights in the first year is limited to three by Shuttle availability. Four additional launches are included for reliability losses. This results in 344 flights for programmatic consideration compared to 357 flights required for 100% capture.



CY	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	Total
WTR	0	0	0	14	13	14	17	14	16	12	12	112
ETR	3*	15	19	13	30	24	24	26	19	27	32	232
Total	3*	15	19	27	43	38	41	40	35	39	44	344

*Limited by Shuttle availability

Fig. 2.4-29 Final Option 3A Annual Flight Summary

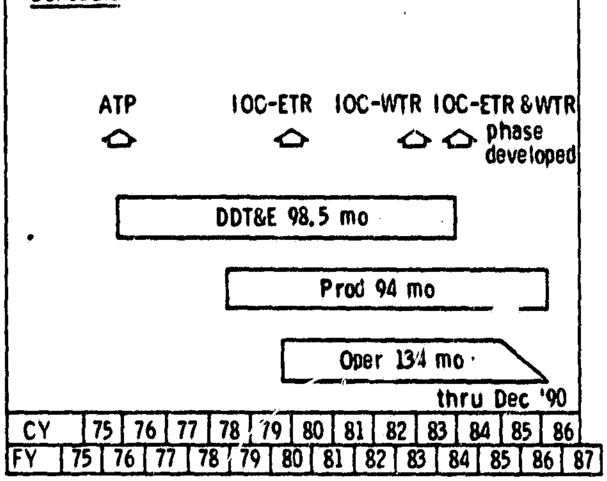
2.4.4.5 Programmatics - NASA programmatics data and results for Final Option 3A are summarized in Fig. 2.4-30. The program is based on completion of preliminary system and subsystem specifications during Phase B, completion of supporting research and technology (SRT) tasks identified for Final Option 3A, 1979 IOC (Phased Tug-Initial) in paragraph 2.6 before the start of DDT&E, and completing Final Option 3A, 1983 IOC (Phased Tug-Final) SRT tasks by October 1, 1978.

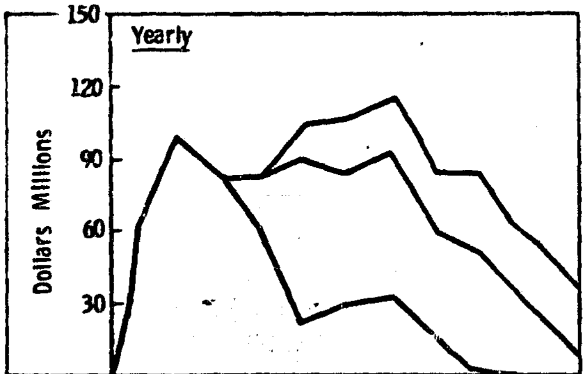
Characteristics

Vehicle:
- Stage-and-a-Half
- Dry Weight: 4004–3820/4043 lb (1816–1733/1834 kg)
- Spacecraft Cap: 4900 lb (2223 kg) del–6500 lb (2948 kg) del/5300 lb (2404 kg) del, 1900 lb (862 kg) retrieval
- Propulsion: High P_c OME–Class I
- Avionics: FSI; current IMU—lightweight IMU, SLR
- Power: Solar array
- Structure: Isolated Ti tanks; Ti, Aℓ & composite body
- Thermal: Passive paint; MLI; base heatshield

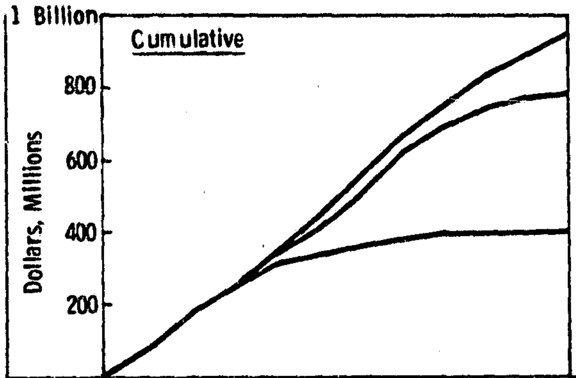
Programmatics:
- Phase Developed
- Launch Operations: 11 years
- Crew Size: 156 ETR + 100 WTR = 256 total
- Number of Flights: 189 NASA + 155 DOD = 344 total
- Fleet Size: 16 Tugs; 5 KS 10; 4 KS 10/1.5; 292 drop tanks

Schedule





FY	76	77	78	79	80	81	82	83	84	85	86
DDT&E	59	98	84	48	19	29	31	12	1		
Prod				36	72	72	66	47	50	30	15
Oper					17	19	22	29	32	31	32
Total	59	98	84	84	108	120	119	88	83	61	47



FY	76	77	78	79	80	81	82	83	84	85	86	90
DDT&E	59	157	241	289	308	337	368	380	381	380	381	381
Prod				36	108	180	246	293	343	373	388	388
Oper					17	35	59	88	120	152	184	327
Total	59	157	241	325	433	554	673	761	844	905	953	1096

Fig. 2.4-30 Final Option 3A Programmatics Summary

Because no kick stages are required before 1982, basic engineering is delayed until near completion of main-stage engineering for the Phased Tug-Initial configuration.

The first Tug is built during DDT&E, and the remaining 15 are built during production. Production completion is controlled by drop-tank build. The Phased Tug Final configuration changes will be developed in DDT&E and all delivered hardware will be built during production.

Because an operational spacecraft is planned for the first launch, the operations program starts two months before first launch. Sixteen main stages, nine expendable kick stages, and 292 expendable drop tanks are used for 344 flights. Eight main stages are expended and four are lost due to reliability problems. Shuttle availability limits the number of flights in 1980 to three.

The Final Option 3A Tug program schedule and associated planning discussion is in Vol 8.0, Section I, para 1.0, and Section II, para 7.0 of the *Selected Option Data Dump* (Ref 5.8). Detailed program cost data are in Vol 8.0, Section II and the appendix to Vol 8.0.

2.4.4.6 <u>Sensitivity Studies</u> - See paragraphs 2.4.2.6 and 2.4.3.6.

2.4.5 Final Option Configuration Summary

Table 2.4-1 summarizes the selected Space Tug configurations, including their capability and subsystem make-up, for each of the four final options. System and subsystem designators, assigned during earlier phases of the Space Tug Study, are shown for continuity and clarification.

Because safety, ground operations, flight operations, and Orbiter interfaces are largely common to all final options, these are presented only once in para 2.5.

Table 2.4-1 Final Option Configuration Summary

Item	Final Option 1	2		3			3A		
Configuration Designator	IA3-2	IA2-3	IA2-4	IA2-8	IA2-3	IA2-4	IVG-1	IVG-2	IVG-3
Capability	1979 Delivery	1983 D/R	1983 Delivery	1979 Delivery	1983 D/R	1983 Delivery	1979 Delivery	1983 D/R	1983 Delivery
Development	Direct	Direct	Direct	Direct	Phase Dev IA2-8	Phase Dev IA2-8	Direct	Phase Dev IVG-1	Phase Dev IVG-1
Payload Delivered lb (kg) (geostationary)	3800 (1724)	4900 (2223)	6000 (2722)	4400 (1996)	4900 (2223)	6000 (2722)	4900 (2223)	5300 (2404)	6500 (2948)
Payload Retrieved lb (kg) (geostationary)	None	1800 (816.5)	None	None	1800 (816.5)	None	None	1900 (862)	None
Mission Duration	36 hr	7 days	7 days	7 days	7 days	7 days	7 days	7 days	7 days
Main Engine (P_c)	OME (150)	Class I (800)	Class I (800)	OME (240)	Class I (800)	Class I (800)	OME (240)	Class I (800)	Class I (800)
Thrust lb (N) / I_{sp} sec (N-sec/kg)	7,500 (33,362) / 327 (3207)	12,000 (53,379) / 338 (3315)	12,000 (53,379) / 338 (3315)	12,000 (53,379) / 330 (3236)	12,000 (53,379) / 338 (3315)	12,000 (53,379) / 338 (3315)	12,000 (53,379) / 330 (3236)	12,000 (53,379) / 338 (3315)	12,000 (53,379) / 338 (3315)
ACPS Capacity lb (kg)	300 (136)	600 (272)	300 (136)	300 (136)	600 (272)	300 (136)	300 (136)	600 (272)	300 (136)
Power Source	Battery	Solar Array	Solar Array	Solar Array	Solar Array	Solar Array	Solar Array	Solar Array	Solar Array
Power to Payload (W)	None	300	300	300	300	300	300	300	300
Avionics Package	AV-9(4)	AV-2	AV-3	AV-1	AV-2	AV-3	AV-1	AV-2	AV-3

Note: Tug is baselined at Autonomy Level II.

2.5 SPECIAL EMPHASIS

Safety, ground operations, flight operations and Orbiter interfaces are generally similar for each of the final operations described in Section 2.4; therefore, to avoid duplication, each is treated here as it relates to all final options.

2.5.1 Safety

2.5.1.1 Program Guidelines - The System Safety Program Guidelines established for the Space Tug Systems Study (Storable) are consistent with Section V, *Data Package, Space Tug System Studies* (Ref 5.12). Potentially hazardous situations were to be identified for Tug configurations, including consideration of all mission phases and Tug/Orbiter/spacecraft interactions. Hazard identification was goverened by a broad interpretation of the hazard definition of MIL-STD-882 (Ref 5.31) i.e., "Any real or potential condition that can cause injury or death to personnel, or damage to or loss of equipment or property." Key considerations in eliminating or controlling hazardous situations were the hazard reduction precedence sequence of NHB 5300.4 (ID) (Ref 5.21), design for minimum hazard, use safety devices, use warning devices, or develop special procedures. In practice, each identified hazard is evaluated to obtain optimum safety consistent with Tug requirements. In addition to incorporating safety In addition to incorporating safety features in Tug configuration options, safety criteria and requirements were to be developed for later program phases.

2.5.1.2 Safety Approach - The initial systems study safety approach (Task 2 and Task 3) consisted of applying the *Data Package, Space Tug System Studies,* (Ref 5.12) to all areas of design and operational planning. System safety criteria in Ref 5.12 were used as trade study drivers, as appropriate.

The approach for Final Options 1, 2, 3 and 3A in Task 5 included a formal system safety analysis, including potential hazard identification, followed by analysis to establish the hazard level and control requirements. The analysis results are used to further reduce hazard levels. Hazard analysis is considered to have two levels: 1) hazard assessment or preliminary hazard analysis appropriate for a study phase; 2) a detailed analysis, an iterative process from early phases through final design. Hazard levels were assigned to each hazard analyzed (catastrophic, critical, or controlled) in accordance with the definitions below.

"HAZARD LEVELS - A hazard whereby environment, personnel error, design characteristics, procedural deficiencies, or subsystem malfunction may result in loss of personnel capability or loss of system shall be categorized as follows:

a. *Catastrophic* - No time or means are available for corrective action.

b. *Critical* - May be counteracted by emergency action performed in a timely manner.

c. *Controlled* - Has been counteracted by appropriate design, safety devices, alarm/caution and warning devices, or special automatic/manual procedures."

All hazards that cannot be reduced to a "controlled" level are considered residual hazards and are tracked while effort continues to reduce the hazard level. The analysis further provides hazard control criteria/requirements for both design and operational planning.

2.5.1.3 Summary and Conclusions - Table 2.5-1 summarizes the Task 5 safety analysis for each final option and the kick stages. For further information and a detailed breakdown of this summary, see Vol 7.0 of the *Selected Option Data Dump* (Ref 5.8).

Table 2.5-1 System Safety Summary

System Safety Activity	Final Option			Kick Stages
	1	2 & 3	3A	
POTENTIAL HAZARD IDENTIFICATION				
FMEA*				
Criticality 1 SFPs	6	6	12	2
Criticality 2 SFPs	26	28/31	49/53	4
Ground Operations Analysis				
Catastrophic (Functions)	8	8	8	6
Critical (Functions)	32	32	32	5
Checklist Discrepancies				
System Safety	6	6	6	0
Operational Safety	2	2	2	--
COMPOSITE HAZARDS LIST				
Potential Hazard Sources	15	15	16	9
Hazardous Conditions	17	17	18	11
HAZARD ASSESSMENT				
Catastrophic	6	6	6	3
Critical	15	15	15	6
DETAILED HAZARD ANALYSIS**				
Catastrophic	2	2	2	—
Critical	6	6	6	2
Controlled	3	3	3	—
RESIDUAL HAZARDS				
Pending Detail Design &/or Procedures	5	5	5	1
Pending Risk Management Decision	3	3	3	1

*The dual number of SFPs indicates "Delivery Only/Delivery-Retrieval."

**The hazard analysis is a continuing iterative process through all program phases.

The table indicates the number of potential hazards in each final option and results of the detailed hazards analysis. Residual hazards fall into two categories: 1) the majority are those that can normally be expected to be reduced to a controlled level by application of known detail design and/or procedural constraints, such as propellant system design and transfer procedures; 2) three residual hazards that require risk management decisions. Two of the latter, classified as critical, concern the use of a common pressurization source for fuel and oxidizer and the lack of ACPS propellant dump capability. The third, classified as catastrophic, concerns the unlikely simultaneous rupture of both propellant tanks during handling after loading. This hazard requires detailed handling equipment design, handling procedure verification, and acceptance by NASA.

Of primary safety concern were the storable propellants, and the safety analysis focused on these to identify properties, history (tanks and pressure vessels on Titan II/III), leak data, spill data, and other safety considerations. The long history of use and proven design and handling procedures leads to the conclusion that storable propellants can be used safely and effectively for the Tug.

Another safety concern is the simultaneous dumping of propellants during ascent abort. To prevent a high-order propellant interaction, simultaneous propellant dumping should be limited to above 150,000 feet (47,720 m). At or above that altitude, the interaction is at a very low order and is considered safe.

Although there are potential hazards in the design concepts (as in all aerospace vehicle designs) they can be reduced to an acceptable risk level. The preliminary system safety analysis, plus previous experience, provides the conclusion that final-option design concepts are safety manageable.

2.5.1.4 <u>Methods</u>

2.5.1.4.1 <u>Task 2 Subsystem Analysis</u> - As stated, the Task 2 effort was not a formal safety analysis. However, the safety criteria in Ref 5.12 were applied to the subsystem selection and synthesis process; e.g., the ACPS was design to be fail-operational/fail-safe because of safety requirements, and all candidates not meeting this requirement were rejected. For further details, see page III-10a of the *Systems Detailed Assessment Briefing Addendum* (Ref 5.6).

2.5.1.4.2 <u>Task 5 Program Definition</u> - Several analyses were performed to identify hazards, which were then subjected to hazards analyses to determine the criticality of each:

a. *Failure Mode and Effects Analysis* - Each subsystem was analyzed to identify all Category 1 (crew hazard) single-failure point (SFP) and all Category 2 (mission hazard) SFPs. Each SFP was identified as a potential hazard.

b. *Ground Operations and Maintenance Task Analysis* - Each ground operations and maintenance task was analyzed to define hazardous operations and determine the criticality of the hazards in accordance with NHB 5300.4 (1D) (Ref 5.21). Each hazardous operation identified was considered a potential hazard.

c. *System Safety Design Checklist* - The safety criteria of the study *Data Package* (Ref 5.12), Skylab design checklists (Ref 5.23), *AFSC Design Handbook DH1* (Ref 5.32), *MSC Space Flight Hazards Catalog MSC 00134* (Ref 5.22), and Martin Marietta experience were the basis for a Tug system design safety checklist given to subsystem designers to indicate compliance or noncompliance. All noncompliance responses were considered potential hazards.

d. *Operational Safety Checklist* - The NAR *Safety in Earth Orbit* report (Ref 5.37) and Martin Marietta experience were the basis for a Tug system operational safety checklist given to operations and subsystem design personnel to indicate compliance or noncompliance. All noncompliance responses were considered potential hazards.

e. *System Safety Evaluation* - Each subsystem was independently examined by a systems safety engineer to identify potential hazards, using a hazard identification checklist (acceleration, chemical energy, contamination and potential hazards identified.

f. *Storable Propellant Evaluation* - Proposed propellants were examined, their properties identified, their history (data from more than ten years of Titan experience) summarized, and the safety concerns documented.

All hazards identified by these analyses were entered in a potential hazard matrix (Table 2.5-2 is a sample.), which was the basis for the detailed hazard analyses.

g. *Detailed Hazard Analyses* - These were performed to describe the hazards, identify potential effects, describe analysis assumptions, define hazard control requirements, and determine disposition of the hazard. (Table 2.5-3 is a single actual hazard analysis.)

h. *Hazard Catalog* - A hazard catalog was prepared to identify and status the hazards analyzed. Hazard status categories are: eliminated, residual, hazard level (per NHB 5300.4(1D)), accepted (by NASA management) and open. Residual hazards are individually cataloged, giving description and recommendation. Table 2.5-4 shows a hazard catalog hazards list and Table 2.5-5 is a single actual hazard catalog, Part II - residual hazards.

*Table 2.5-2 Sample Potential-Hazard Matrix**

POTENTIAL HAZARD MATRIX

PROGRAM/PHASE: SPACE TUG (STORABLE)/SYSTEMS STUDY

SYSTEM: A - SINGLE STAGE TUG
I - MAIN PROPULSION

DATE: 8/15/73

PAGE: A1-1

SUBSYSTEM/ COMPONENT	TRANSPORTATION & HANDLING	PREFLIGHT OPERATIONS	LAUNCH OPERATIONS	ORBITER FLIGHT	TUG DEPLOYMENT/ RETRIEVAL	TUG FREE FLIGHT	PAYLOAD DEPLOYMENT/ RETRIEVAL	POSTFLIGHT OPERATIONS	ABORT	OTHER ANALYSES: FMEA/SFP	OTHER ANALYSES: OPERATIONS & MAINTENANCE	OTHER ANALYSES: SYSTEM SAFETY CHECKLIST
1. General												
1.1 Propellants			2 (1.005)	2 (1.005)	2 (1.005)			3 (1.005)				
1.1.1 Oxidizer, N_2O_4		2,8,14 (1.001)	2,8,14 (1.001)	2,8 (1.001)	2,8 (1.001)	2 (1.001)		2,8,14 (1.001)	2,8,14 (1.001)		2.2.7 3.1.1	
1.1.2 Fuel, MMH		2, 14 (1.002)	2,14 (1.002)	2 (1.002)	2 (1.002)	2 (1.002)		2, 14 (1.002)	2,14 (1.00[illegible]			
1.2 Propellant Tanks	1,2,14 (1.004) 11 (1.003)	11 (1.003)	11 (1.003)									
1.2.1 Oxidizer Tank												
1.2.2 Fuel Tank												

* From Vol 7.0 *Selected Option Data Dump* (Ref 5.8)

*Table 2.6-3 Sample Hazard Analysis**

HAZARD LEVEL	Critical	NO.	1.001 R1
STATUS	Open	PAGE	1 of 3
PROGRAM PHASE	Systems Study	DATE	8/15/73

SYSTEM: I - Main Propulsion SUBSYSTEM: Oxidizer, N_2O_4

OPERATION/PHASE: All

HAZARD GROUP: 8-Material Deterioration, 14-Toxicant

REFERENCES: AFSC DH 1-6, AFM 160-39, KSC GP-359

HAZARD DESCRIPTION:
Nitrogen tetroxide, N_2O_4, is a corrosive, highly toxic oxidizing agent. It is non-flammable in air but supports combustion and is hypergolic with the hydrazines. The hazardous effects result when N_2O_4 is released by leaks or spills.

POTENTIAL EFFECTS:
1. Liquid nitrogen tetroxide in contact with organic materials may cause fires.
2. Vapors are extremely toxic to breathe. Low concentration that may be inhaled without discomfort may cause serious damage to the lungs. (Continued on Page 2)

ASSUMPTIONS/RATIONALE:
1. N_2O_4 proposed for use on the Space Tug is designated MON-1 by MIL-P-26539C having a green color and is nominally 99% N_2O_4, 0.8±0.2% NO and 0.17% water. The material is an equilibrium mixture of N_2O_4 and nitrogen dioxide (NO_2).
2. Nitrogen tetroxide is not sensitive to mechanical shock, heat or detonation.
3. Nitrogen tetroxide is soluble in water, forming nitric acid and nitrous acid. The latter decomposes to form additional nitric acid and evolves oxides or nitrogen.

(Continued on Page 2)

HAZARD CONTROL REQUIREMENTS:	REFERENCE
A. Design	
1. Separate incompatible fluid systems to prevent inadvertent mixing.	DCL-53
2. Design adjacent incompatible systems so that it is impossible to interconnect them.	DCL-54
3. Hypergolic fuels shall not be separated by <u>only</u> a single weld.	DCL-57
4. Inhibit N_2O_4 with NO to prevent corrosion of titanium.	DCL-60
5. Provide personnel showers and eye wash in propellant transfer area.	
6. Provide facility vapor burners for vapor disposal.	
7. Provide a separate area (tank) for retention/neutralization of waste oxidizer.	

(Continued on Page 3)

DISPOSITION:
1. Entered in Hazard Catalog.

ORIGINATOR/LOCATION:
W. R. O'Halloran, Ext. 4203

* From Vol 7.0 *Selected Option Data Dump* (Ref 5.8)

NO.	1.001 R1
PAGE	2 of 3
DATE	8/15/73

(LIST ADDITIONAL CONTENT IN THE ORDER OF SHEET 1)

POTENTIAL EFFECTS:

3. Nitrogen tetroxide contacting the skin causes severe burns.
4. Nitrogen tetroxide contacting the eyes may cause permanent damage.
5. Concentrated nitrogen tetroxide vapor contacting the skin may cause burns.
6. Low concentration of vapor contacting the skin may cause a yellowing of the skin.

ASSUMPTIONS/RATIONALE:

4. The physical properties of N_2O_4 include:

Boiling point	70.1°F (21.2°C)
Freezing point	11.84°F (-11.2°C)
Density at 68°F (20°C)	12.08 lb/gal (1421 kg/m^3)
Critical temperature	316.8°F (158.2°C)
Critical pressure	1455 psig (1003 N/cm^2)
Vapor pressure at 90°F (32.2°C)	10 psig (6.9 N/cm^2)

5. The Threshold Limit Value (TLV) for NO_2 has been established as 5.0 ppm. The TLV establishes the threshold limit for 8 hours per day, 5 days a week. Emergency tolerance limits established by the National Academy of Sciences, National Research Council Committee on Toxicology, are:

   35 ppm for 5 minutes
   25 ppm for 15 minutes
   20 ppm for 30 minutes
   10 ppm for 60 minutes

6. If a spill or leak occurs, vaporization is dependent upon agitation, area wetted, ambient temperature, surface temperature and surface porosity. An evaporation rate of 10%/min for N_2O_4 is considered realistic when a spill contacts solar heated surfaces with ambient air temperature above 90°F (32.2°C)

7. The vapor dispersion pattern is dependent on surface and air temperature, wind direction and velocity and ground wind turbulence. A 30° (0.523-rad) cone of dispersion down wind from the source of a spill has been established based on experiments with atmospheric turbulent diffusion. Calculations of toxic vapor exposures can be made based on assumed conditions but the Weather Information Network Display (WIND) system should be employed for dispersion predictions.

8. Both portable and fixed toxic vapor detectors are available that will sense concentrations of 5.0 ppm (TLV) and less.

9. All known spills of propellants have been associated with malfunction of hardware in the operational mode or with personnel activity. Minor spills [50 gallons (0.189 m^3) or less] have occurred in propellant holding areas, but no spills larger than the normal few cubic centimeters that are lost during umbilical disconnect have occurred on launch pads. Minor leaks of airborne hardware have occurred under long term static storage conditions. These leaks were discovered by periodic leak checks using a portable leak detector before hazardous concentrations were reached.

NO.	1.001 R1
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(LIST ADDITIONAL CONTENT IN THE ORDER OF SHEET 1)

ASSUMPTIONS/RATIONALE:

10. Operating procedures have been developed and are in use on Titan II and Titan III programs that control both vapor and liquid. Contingency procedures include neutralization of liquid waste using a sodium hydroxide solution.

11. Nitrogen tetroxide has been used safely on the Titan II and Titan III programs by both MMC and USAF personnel.

12. Detail designs and handling procedures can be developed to reduce the hazard level to Controlled.

REQUIREMENTS:

B. Operations

1. Provide protective clothing for propellant handling personnel.
2. Propellant handlers will be trained and certified.
3. Propellant handlers must pass an annual propellant physical examination.
4. Personnel required to be in the vicinity of contained N_2O_4 will attend a propellant indoctrination lecture annually.
5. Define the propellant handling and loading plan.
6. Operations will be controlled by detailed procedures that have been approved by System Safety.
7. Provide contingency plans to alert and/or evacuate unprotected personnel from areas subject to hazardous vapor concentrations.

Table 2.5-4 *Sample Hazard Catalog Part I, Hazards List**

SECTION: 1 - MAIN PROPULSION PAGE: I-1

HAZARD NO.	HAZARD	ELIMINATED	RESIDUAL	HAZARD LEVEL	ACCEPTED	OPEN
1.001	Highly toxic, corrosive oxidizer, N_2O_4		1.1	Crit.		X
1.002	Highly toxic, flammable/explosive fuel, MMH		1.2	Crit.		X
1.003	Propellant tank ullage overpressure during preflight	X				
1.004	Fire/Explosion from both tanks rupture		1.3	Cat.		X
1.005	Propellant contamination of Orbiter Payload Bay	X				
1.006	Overpressurization of propellant tanks by pressurization system	X				
1.007	Pressurized Helium Sphere		1.4	Crit.		X
1.008	Common Pressure Source		1.5	Crit		X
2.001	Highly toxic, flammable/explosive monopropellant N_2H_4		2.1	Crit.		X
2.002	Pressurized Helium Sphere		2.2	Crit.		X
2.003	ACPS propellant dump capability		2.3	Cat.		X

* From Vol 7.0 *Selected Option Data Dump* (Ref 5.8)

*Table 2.5-5 Hazard Catalog Part II, Residual Hazards**

SYSTEM: I - Main Propulsion	ITEM NO. 1.1
SUBSYSTEM: Oxidizer, N_2O_4	HAZARD LEVEL Critical
COMPONENT: N/A	DATE 8/1/73

HAZARD DESCRIPTION:

Nitrogen Tetroxide, N_2O_4, is a corrosive, highly toxic oxidizing agent. It is nonflammable in air but supports combustion and is hypergolic with the hydrazines. N_2O_4 in contact with organic materials may cause fires. Health hazards include skin and eye burns from liquid or vapor, and the extreme toxic effects of breathing vapor.

RECOMMENDATION:

1) Since N_2O_4 has been used safely on Titan II, Titan III, and Apollo, it is recommended that N_2O_4 be accepted as the Space Tug storable oxidizer.

2) The hazard level will remain critical until hardware build and approved detail operating procedures demonstrate the hazard is controlled.

DISPOSITION:

* From Vol 7.0 *Selected Option Data Dump* (Ref 5.8)

2.5.2 Ground Operations - Ground operations consist of vehicle tests, fleet size determination, launch-site operations, logistics, facilities, ground-support equipment (GSE), maintenance and refurbishment, and manufacturing. These subjects are summarized in the following subsections. Details of these subjects are presented in Vol 6.0, Sect. II, and Appendix of the *Selected Option Data Dump* (Ref. 5.8).

2.5.2.1 Ground Rules and Assumptions - Throughout the Space Tug Study, certain assumptions were made to accomplish the operations analyses and determine maintenance concepts and fabrication requirements in parallel with basic conceptual design and configuration definition. Conversely, requirements resulting from these disciplines were levied on the design to ensure testability, maintainability, and, most important, reuseability.

1) Baseline Tug flows assume:

    (a) Propellant loaded off-pad;

    (b) Spacecraft/Tug mate accomplished in Tug maintenance and checkout facility (MCF);

    (c) Tug/Orbiter mate accomplished in Orbiter MCF;

    (d) Tug/Orbiter separation subsequent to flight in Orbiter MCF.

2) Total site operation planning at both KSC and WTR was based on maintaining the Tug refurbishment and prelaunch time, and adjusting crew and fleet size to accommodate the variation in launch rate for each final option.

3) New Tug acceptance will be accomplished in Denver.

4) The expendable Tug in 1990 is the last Tug so that one of the active Tug fleet can be used. Therefore, the number of expendable Tugs built will be one less than expendable missions.

5) KSC and WTR operations will be based on five-day work weeks. The number of shifts per day will vary to meet program needs for each final option.

6) No additional flights or Tugs will be considered as a result of Shuttle aborts, reflights, etc.

7) Tug flights will be limited by Orbiter availability to no more than three in 1980 and no more than 21 in 1981 (Final Options 1, 3, and 3a). The build-up for Final Option 2 is assumed to be:

Flights	1984	1985	1986
KSC	9	18	24
WTR	6	13	17
Total	15	31	41

8) External Tug cleanliness will be class 100,000.

9) The hypergolic loading facility will be shared with OMS.

2.5.2.2 Vehicle Test - Test methods growth, experienced during the last decade and extrapolation through the next two decades, indicate that cost effectiveness in testing with proper priorities, governed by mission criticalities, will be the driving factors. In long-duration many-flight programs like Tug, exhaustive testing of all components, systems, and end items could be performed regardless of criticality. This would involve an extensive and costly test program. Instead, our approach to the Tug test program is to put the emphasis on two areas:

1) Testing new conceptual-design and new-technology hardware during early design phases;

2) Testing for defects in manufacturing workmanship and testing for hardware infant mortality during the flight-Tug production phase.

Component development testing will be accomplished during the design phase to evaluate design feasibility and capability to accomplish its intended function. These tests will be developed to identify and solve potential and actual design problems during the hardware evolution phase. Development testing will consist primarily of extensive performance and limit tests plus selected environmental tests. Qualification testing will be performed on flight-configured components to environments greater than anticipated during a mission in order to assure that the design and fabrication of flight hardware are compatible with flight environments greater than anticipated during a mission.

The Tug development test program requires five separate test vehicles:

1) Static Test Article - Static structure load, ground vibration survey, and other dynamic tests;

2) Thermal Effects Test Model - Thermal balance tests, main engine hot firing, and propulsion systems functional test;

3) Propulsion Test Vehicle - Development propulsion-system flow performance, system compatibility hot firing, ACPS feed-system verification and hot firing;

4) Controls Mockup - Electronic design confirmation and software development;

5) Life Test Article - Demonstrate survivability of tanks and major structure through repeated pressure and dynamic load cycles.

Flight-vehicle testing will commence with the prototype vehicle and will be continued on each flight article. All acceptance testing will be conducted at the contractor's facility before shipment of Tugs to KSC or WTR.

Prototype vehicle acceptance tests will include systems tests--an EMI/EMC test to demonstrate electromagnetic compatibility with Orbiter payload requirements, and a thermal vacuum test closely approximating a typical mission environment, with margin. Flight-vehicle tests include functional demonstration of Tug systems performance, including sensor acquisition tests, vehicle configuration verification to released engineering, and data review.

2.5.2.3 Fleet Size - Total fleet size is determined by three primany factors as discussed in paragraph 2.1.2:

1) Missions accomplished by expending Tugs;

2) Tugs lost due to reliability/malfunction, or other reasons;

3) Active Tugs required to accomplish the mission model in 1990.

It is also based on the premise that the last expendable Tug is one of the active fleet units expended in late 1990.

Other factors that were considered are yearly launch rates and number of Tugs required for the first and subsequent years to accomplish the mission. These factors, though considered during fleet sizing, basically determine the production rate and number of Tugs required at each launch site at any specific time during the program. Considering this, plus the overall cost trade-off, and the fact that, in specific circumstances, it is more economical to expend a Tug than to accomplish the mission by other techniques, the Tug fleet was calculated to be:

Final Option 1 - 15 Tugs;

Final Option 2 - 13 Tugs;

Final Option 3 - 16 Tugs;

Final Option 3A - 16 Tugs.

The active fleet is defined as the Tugs needed at any specific period to accomplish the mission model as it equates to launch rate. More specifically, in the context in which the active fleet is referred to here, it is the number of Tugs required to accomplish the 1990 mission model considering that, in 1990, all expendable Tugs and reliability losses will have been expended.

Figure 2.5-1 is the result of active fleet size analysis using the Tug turn-around time defined in paragraph 2.5.2.4--the typical Orbiter-Tug mission length of seven days and the point of payload integration and payload-Orbiter demate baselined at the Orbiter checkout facility.

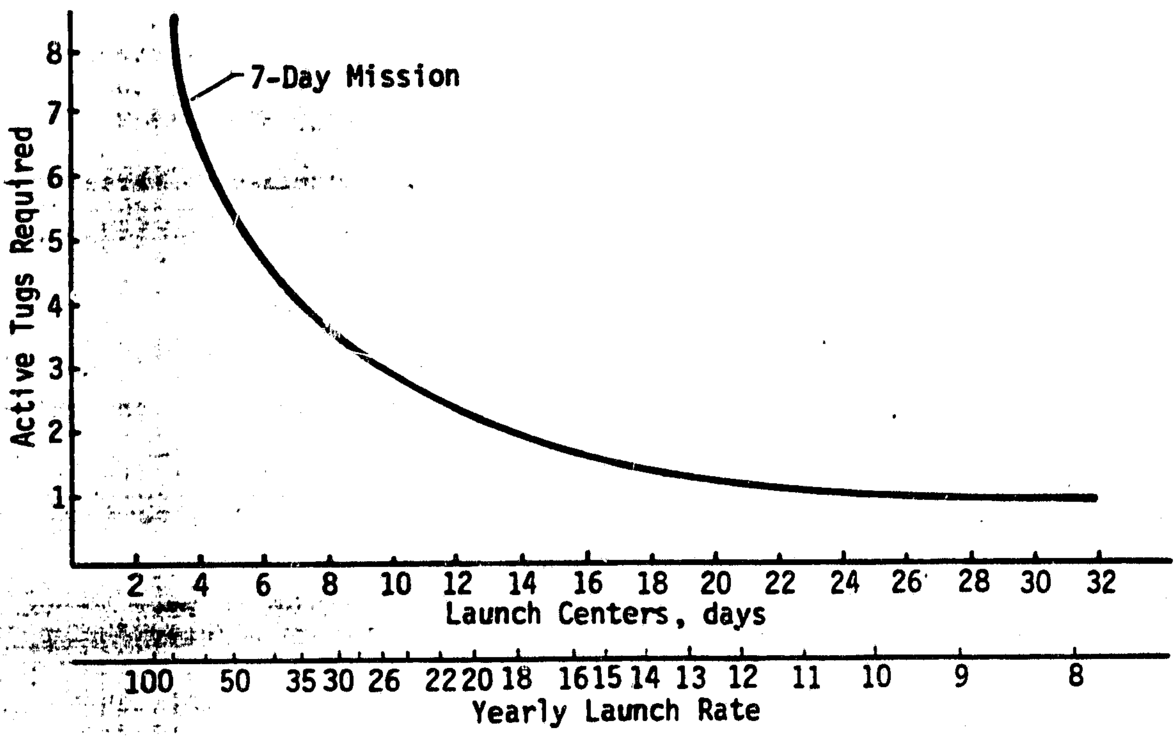

Fig. 2.5-1 Active Fleet Size

2.5.2.4 Launch Site Operations - Launch site operations for the four final options are basically the same, regardless of type of spacecraft or mission requirements, and there is very little effect when the subsystems are modified; i.e., the main engine is changed or the avionics is uprated from a "heavy" system to a lighter "state-of-the-art" system. Basic drivers for all operations are fleet size, launch rate, and location for various integration milestones; i.e., Tug-spececraft mate, Tug-Orbiter mate/demate, and propellant loading. Throughout analysis and costing of various options, a change of IOC was found to have minimal effect on ground operations.

The pre-IOC operational plan for KSC and WTR will be accomplished in two phases, as shown in Figure 2.5-2. Phase I is basic activation of the facility and training of personnel; Phase II will process the first operational Tug through its normal functions.

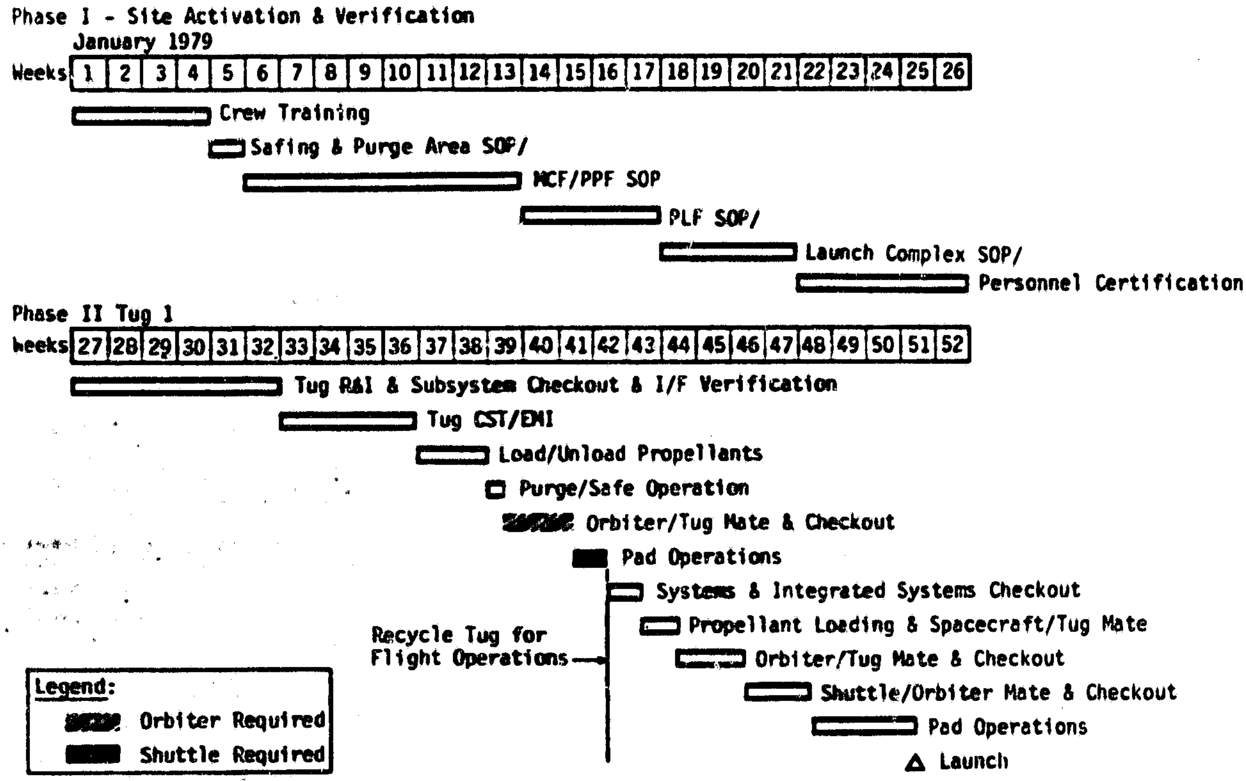

Fig. 2.5-2 Pre-IOC Operations Plan

Launch-site ground turnaround-operations timelines are shown in Figure 2.5-3. Functions timelined are major elements of the Tug launch-site operation. Also included are top-level functional flow times, WBS Level 5 breakout, and tabulation by hour of the number and types of technical personnel needed for ground turn-around functions for one Tug.

The figure shows that it requires 184 hours of Tug operation to turn one Tug around. This time was determined through a detailed analysis of functional activities required on the Tug, accessibility of Tug hardware for test crew access, and its availability for simultaneous testing. Because of access limitations, an increase in crew size will not appreciably reduce the time required. A reduction in crew size will increase the time but could cause an increase in active Tug fleet size to meet launch-center requirements.

Using this functional flow, personnel requirements data, and knowing the launch rate at each launch site, a basic test operations crew size can be developed for each site. This crew/option matrix is shown in Table 2.5-6.

Table 2.5-6 Crew Size Summary

		Final Options							
		1		2		3		3A	
		KSC	WTR	KSC	WTR	KSC	WTR	KSC	WTR
First Year	Support	24	18	24	18	24	34	24	34
	Test	30	30	30	30	30	52	37	66
	TOTAL	54	48	54	48	54	86	61	100
Average 2nd Year through 1990	Support	44	18	44	34	44	34	44	34
	Test	52	30	98	52	98	52	112	66
	TOTAL	96	48	142	86	142	86	156	100

Because the optimum checkout span has been found to be 184 hours for the baselined flow of the Tug, factors that most affect crew size are the size of the active Tug fleet and the launch rate as it varies with each option.

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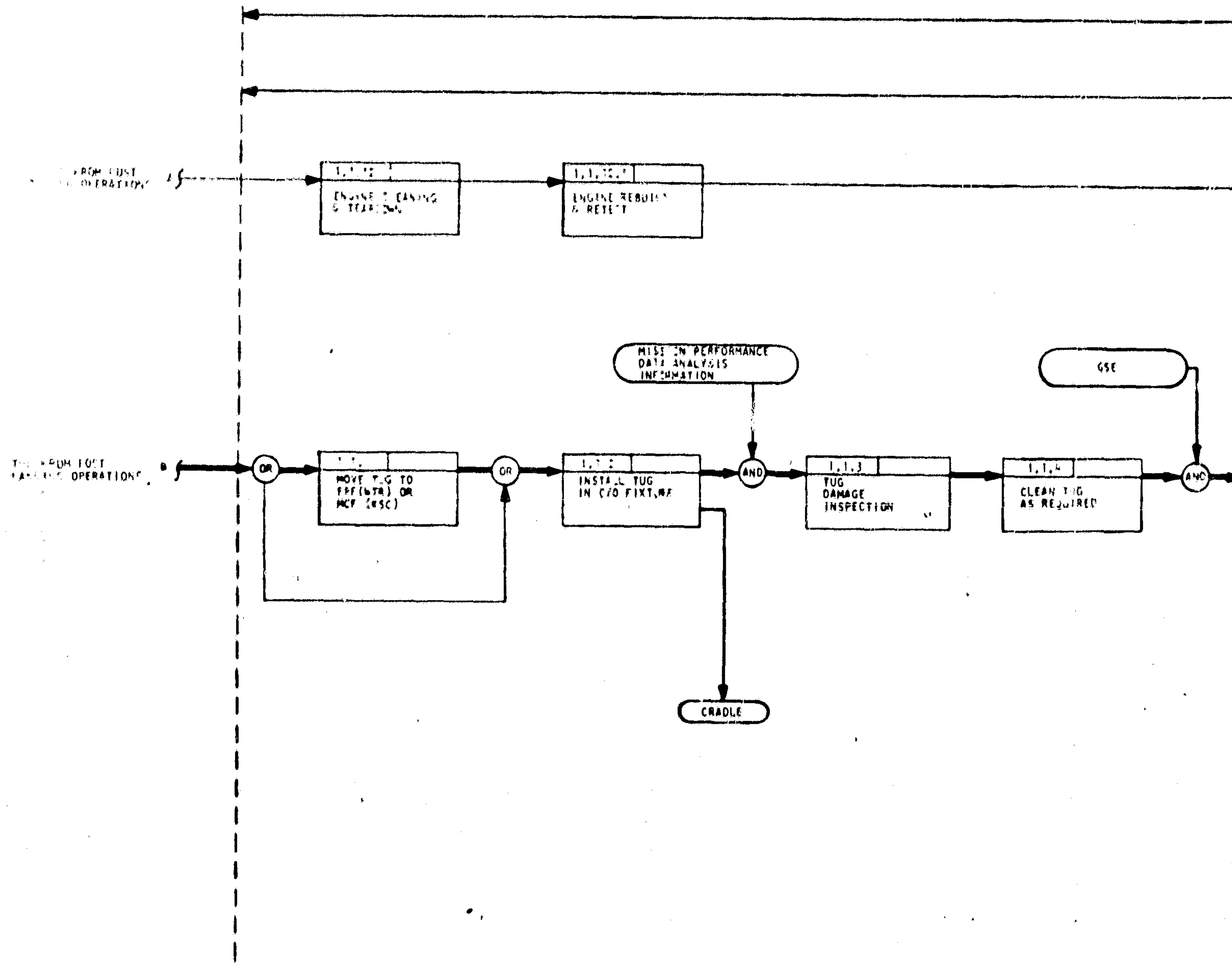

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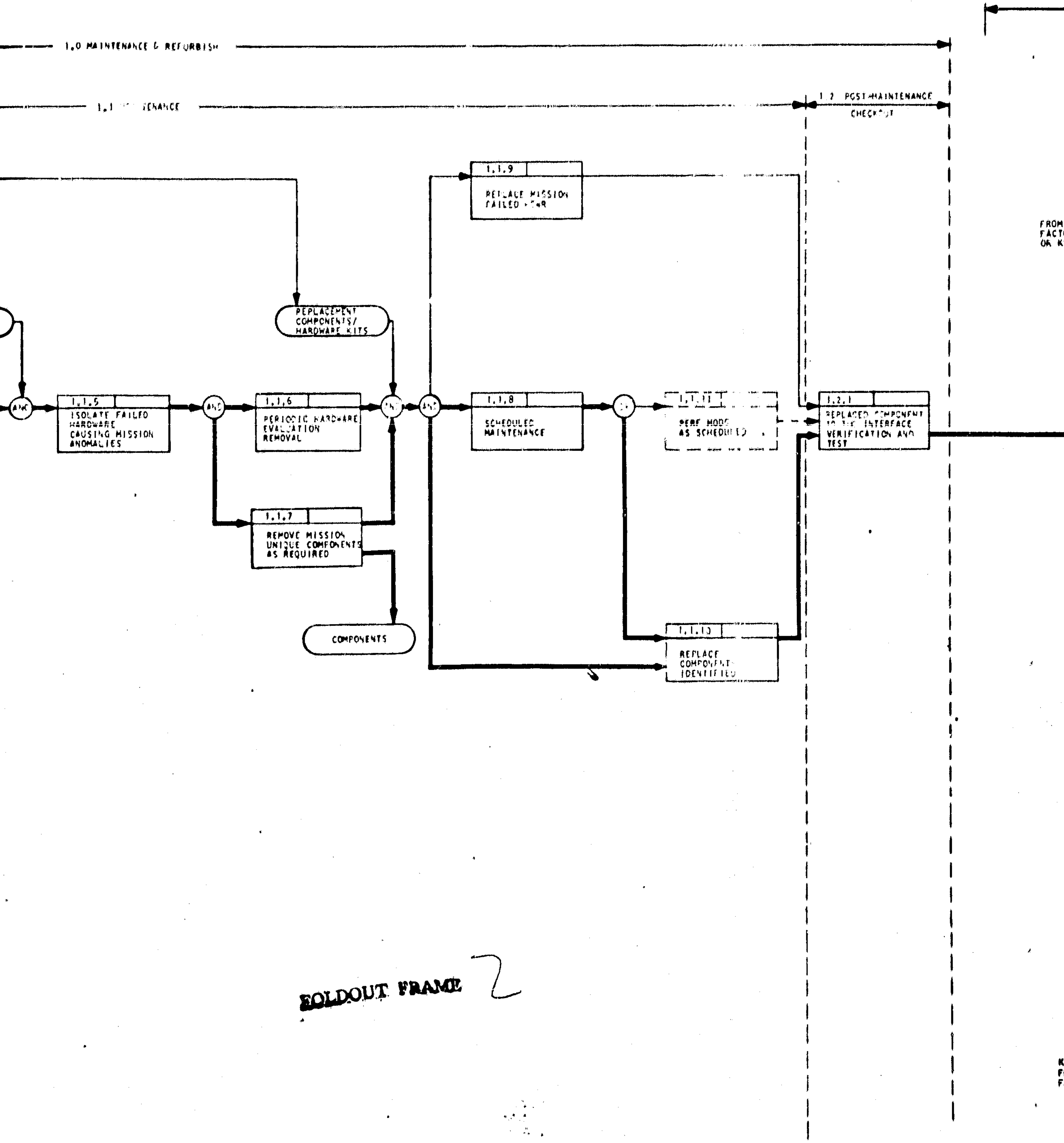

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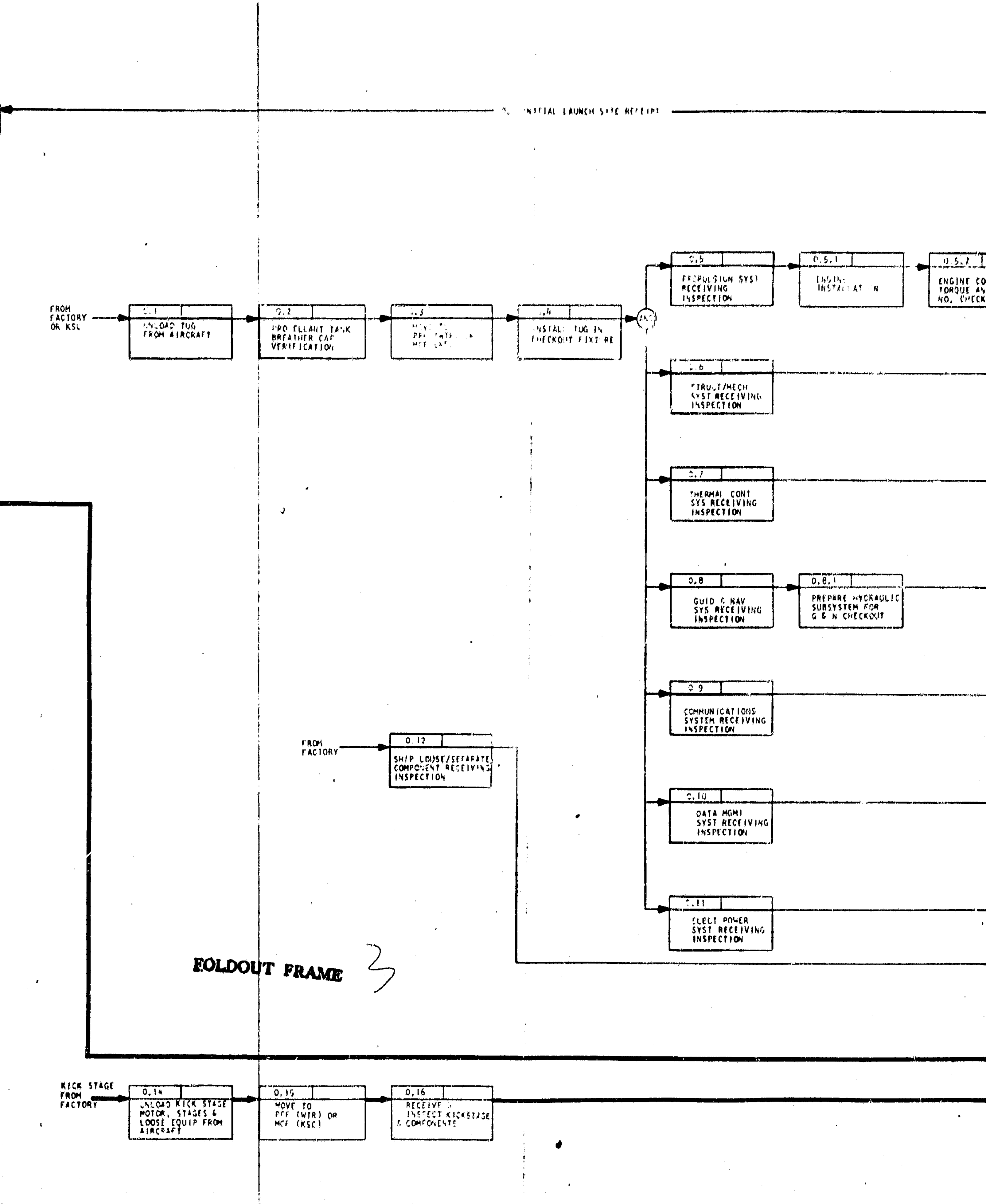

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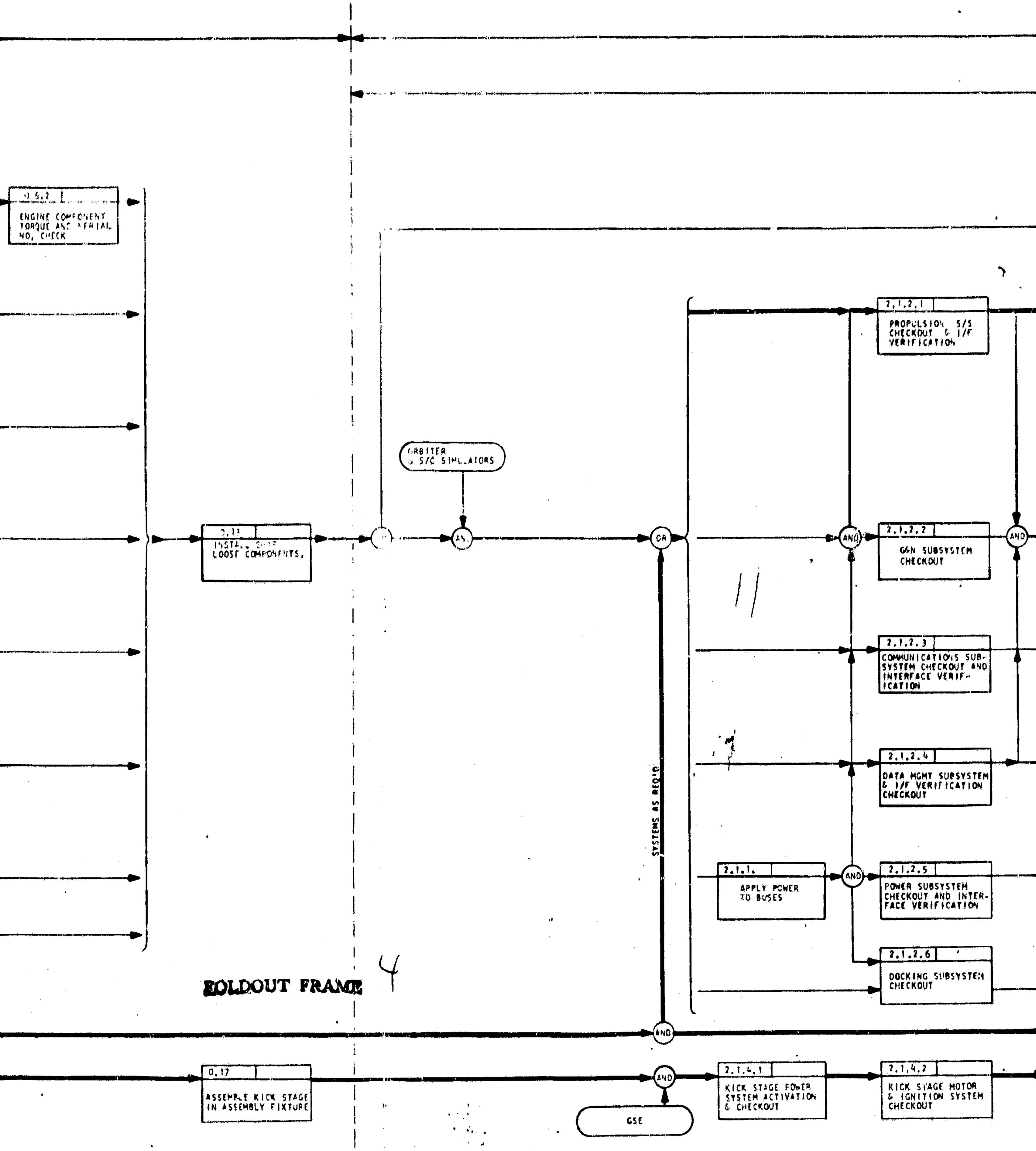
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ENGINE COMPONENT TORQUE AND SERIAL NO. CHECK
0.13
LOOSE COMPONENTS,
ORBITER & S/C SIMULATORS
OR
AND
2.1.2.1
PROPULSION S/S CHECKOUT & I/F VERIFICATION
2.1.2.2
G&N SUBSYSTEM CHECKOUT
2.1.2.3
COMMUNICATIONS SUBSYSTEM CHECKOUT AND INTERFACE VERIFICATION
2.1.2.4
DATA MGMT SUBSYSTEM & I/F VERIFICATION CHECKOUT
2.1.1.
APPLY POWER TO BUSES
2.1.2.5
POWER SUBSYSTEM CHECKOUT AND INTERFACE VERIFICATION
2.1.2.6
DOCKING SUBSYSTEM CHECKOUT
SYSTEMS AS REQ'D
0.17
ASSEMBLE KICK STAGE IN ASSEMBLY FIXTURE
2.1.4.1
KICK STAGE POWER SYSTEM ACTIVATION & CHECKOUT
2.1.4.2
KICK STAGE MOTOR & IGNITION SYSTEM CHECKOUT
GSE
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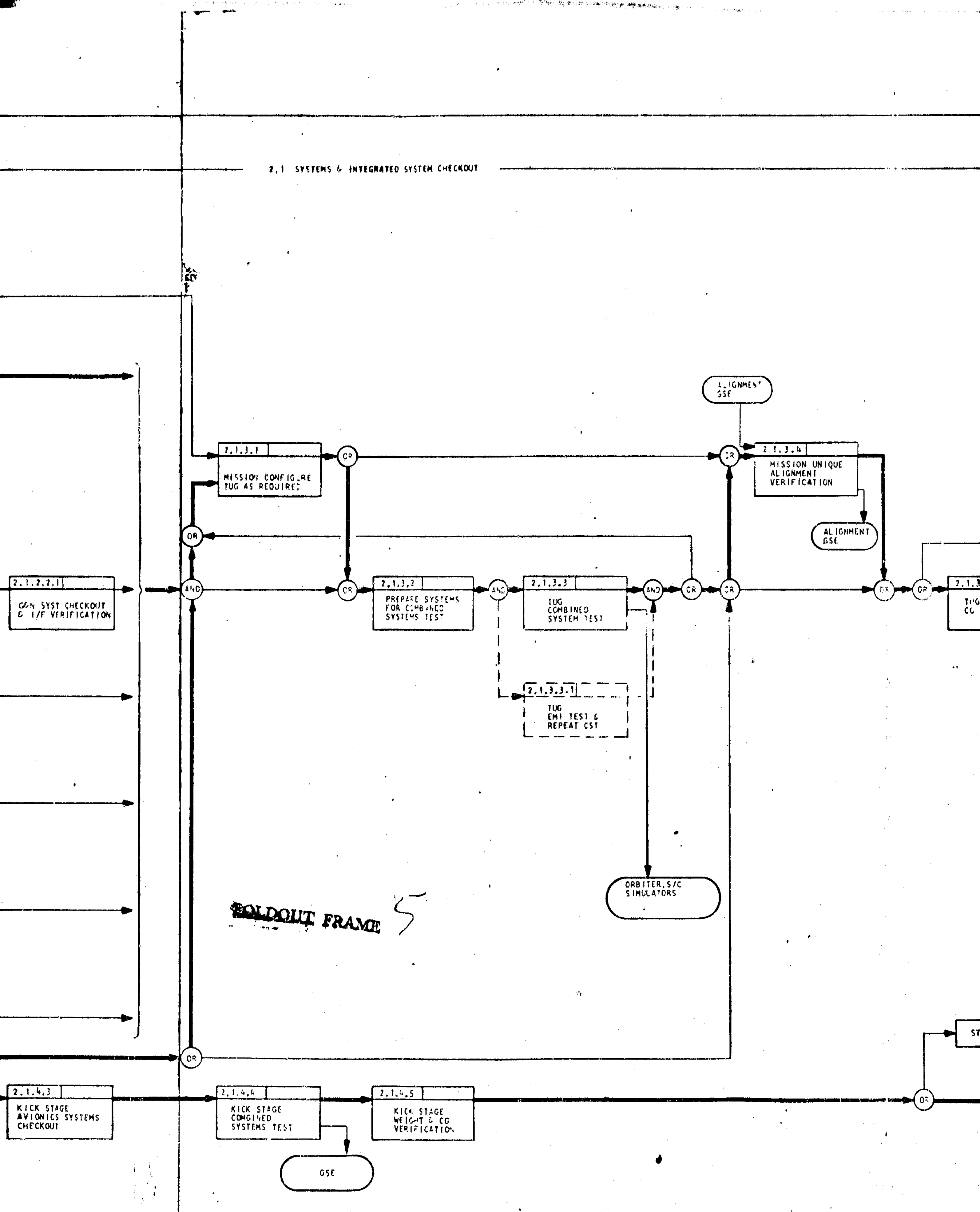

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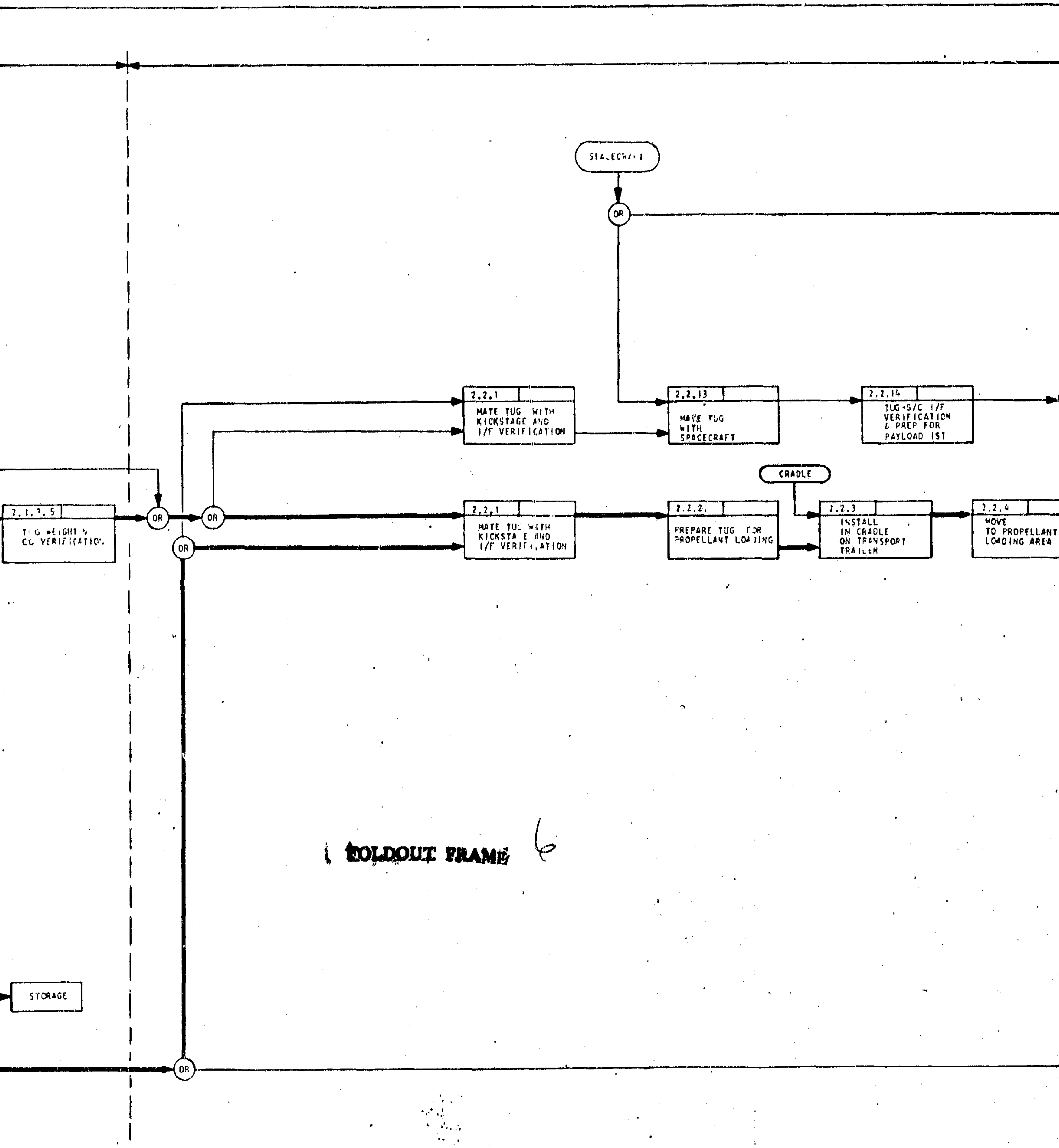

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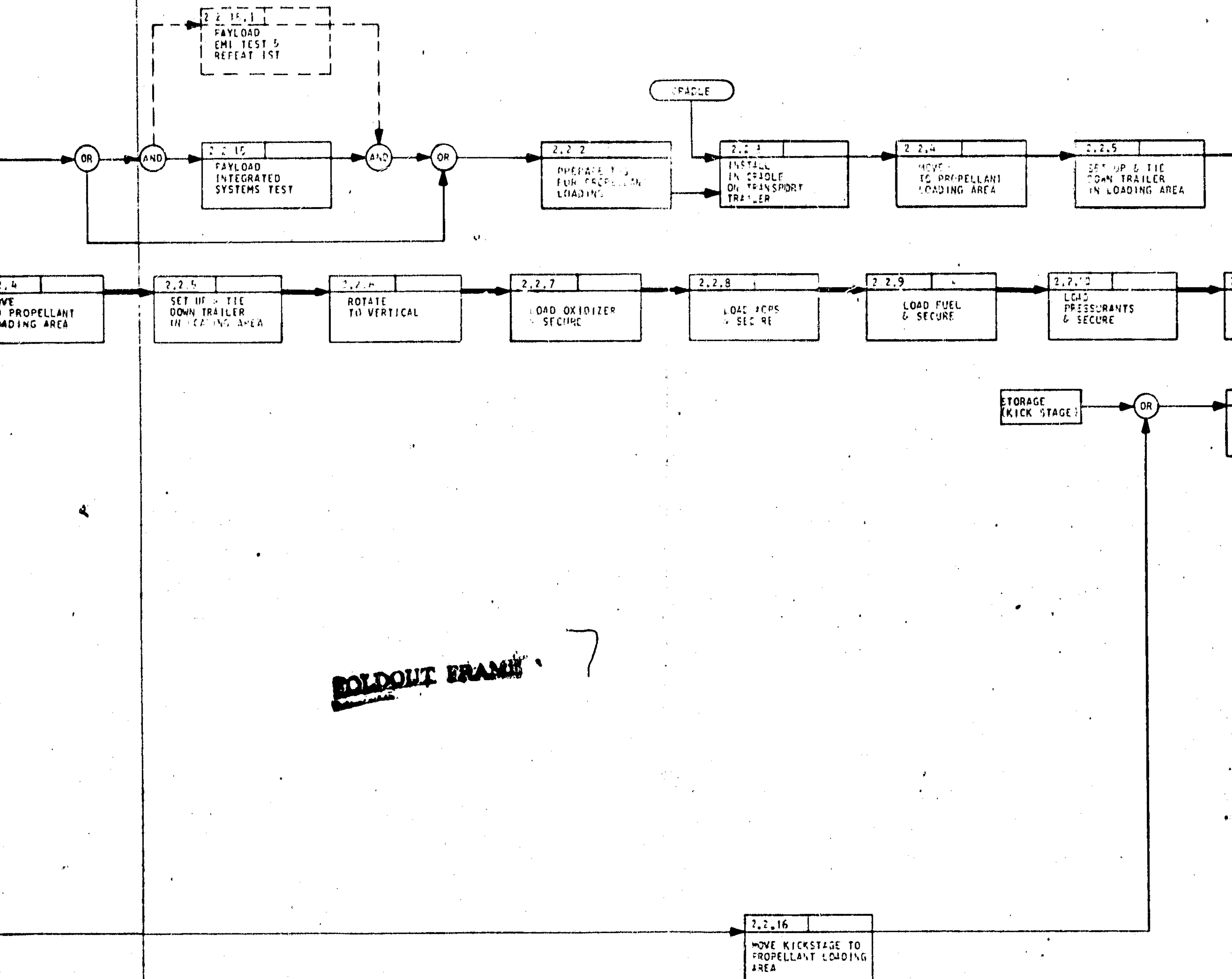
2.2 SPACECRAFT/TUG MATE &



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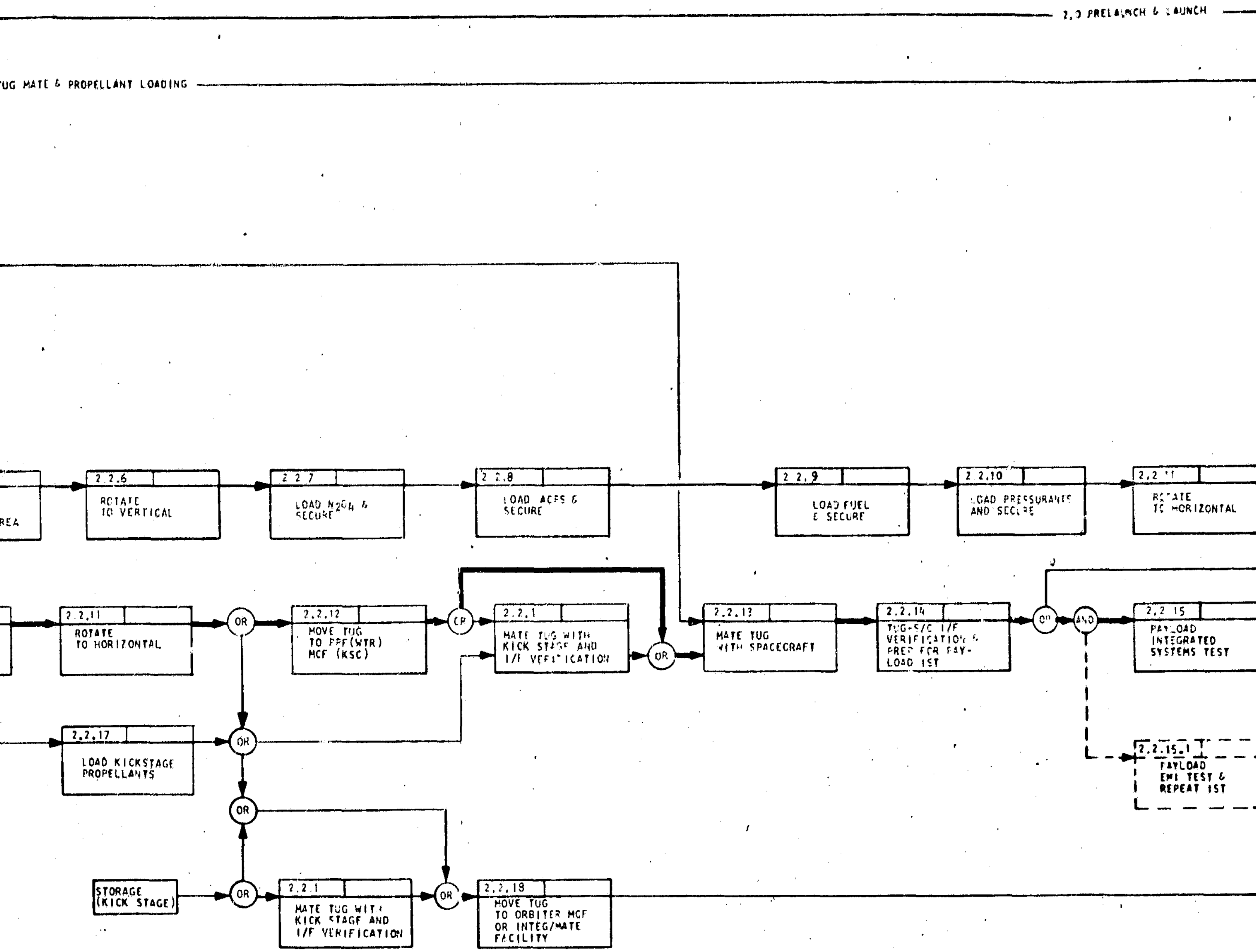

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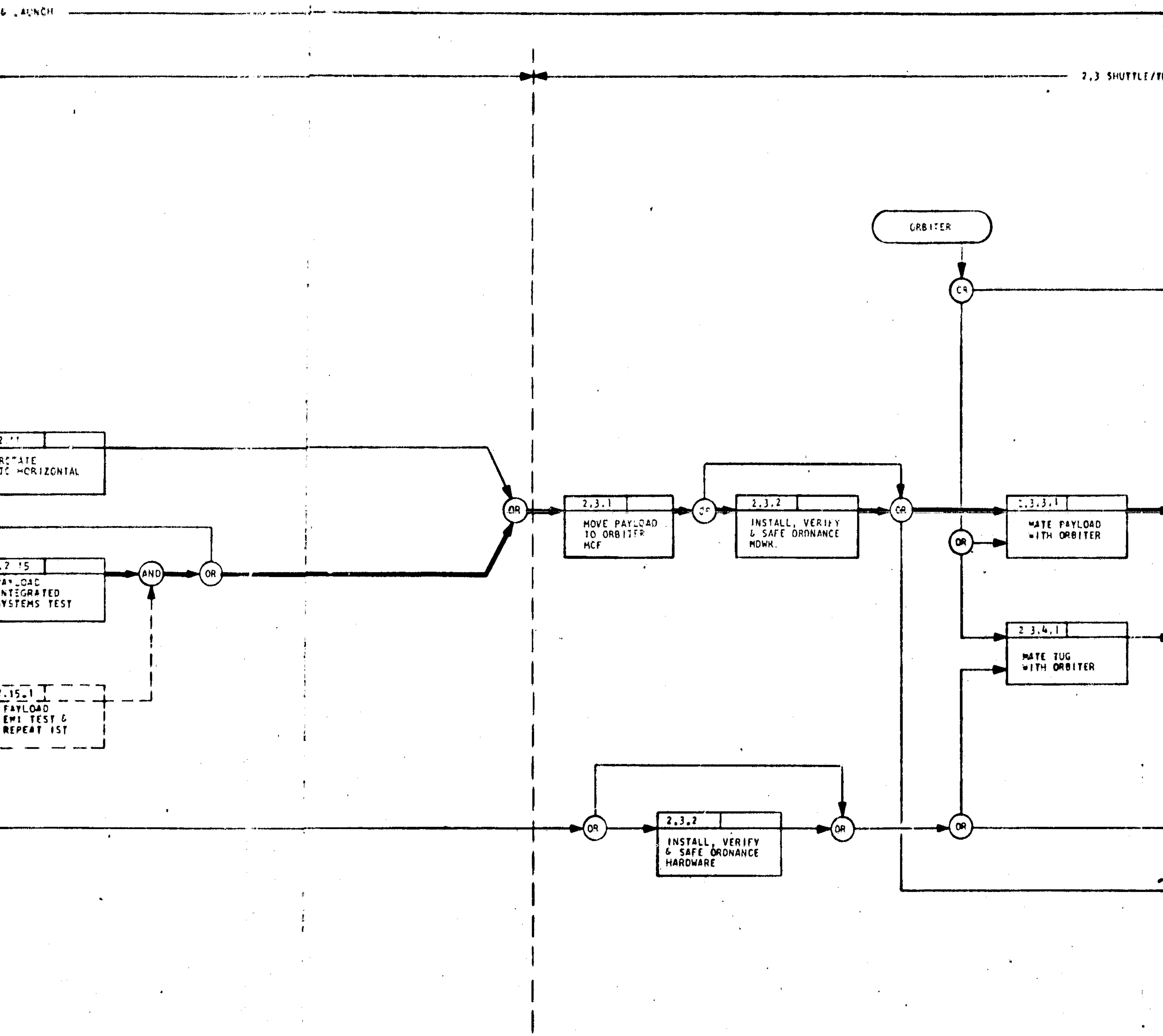

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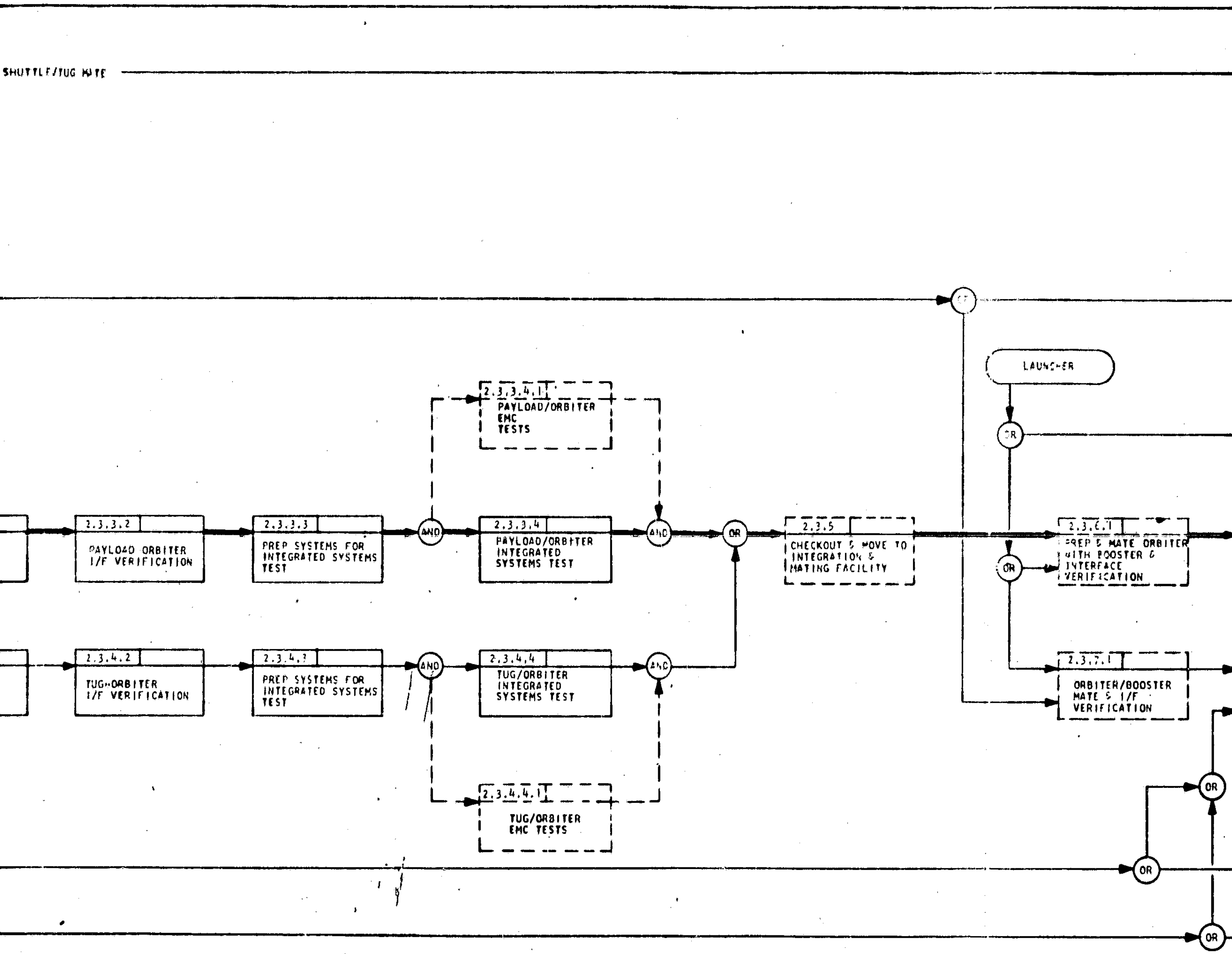

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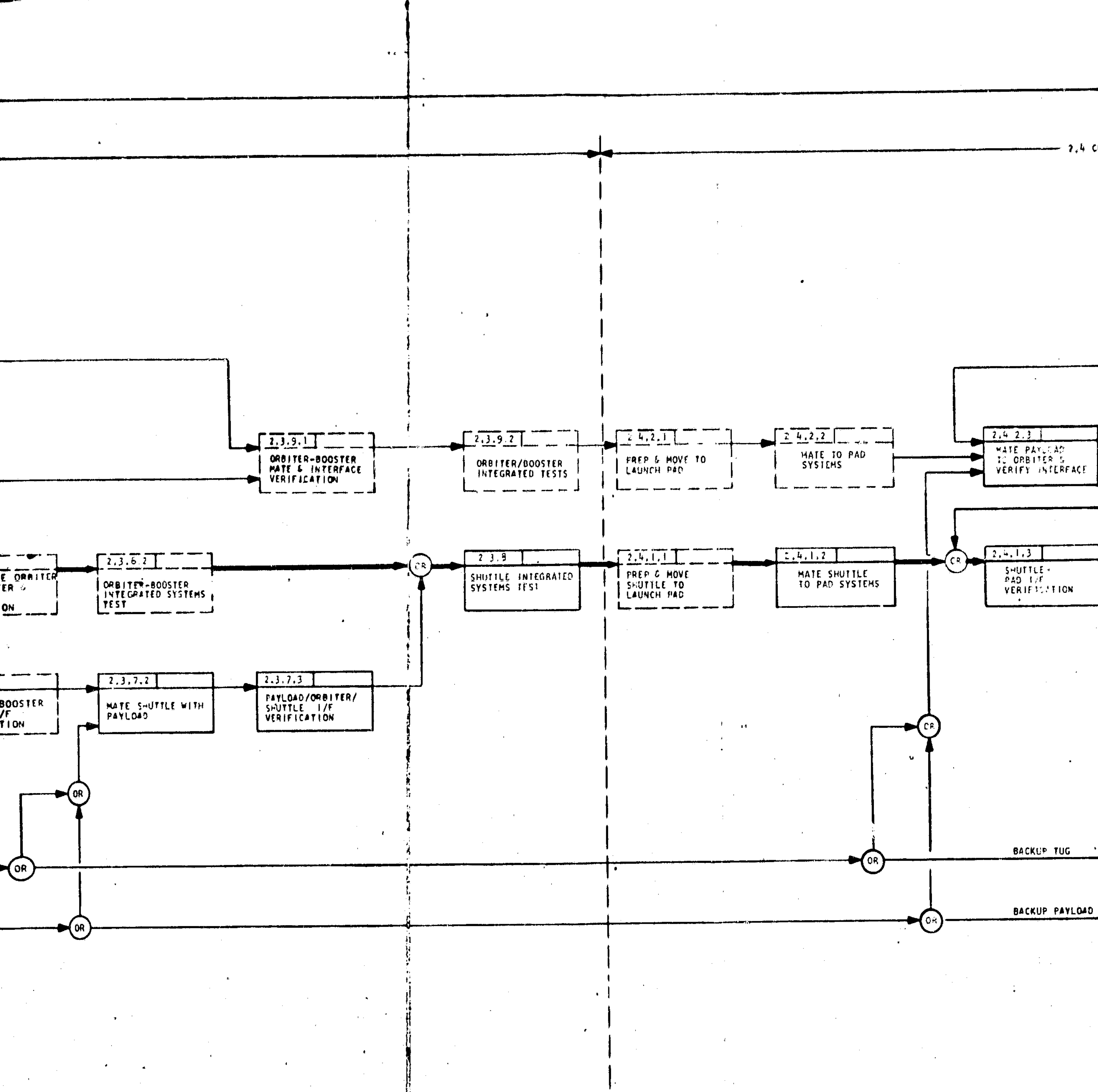

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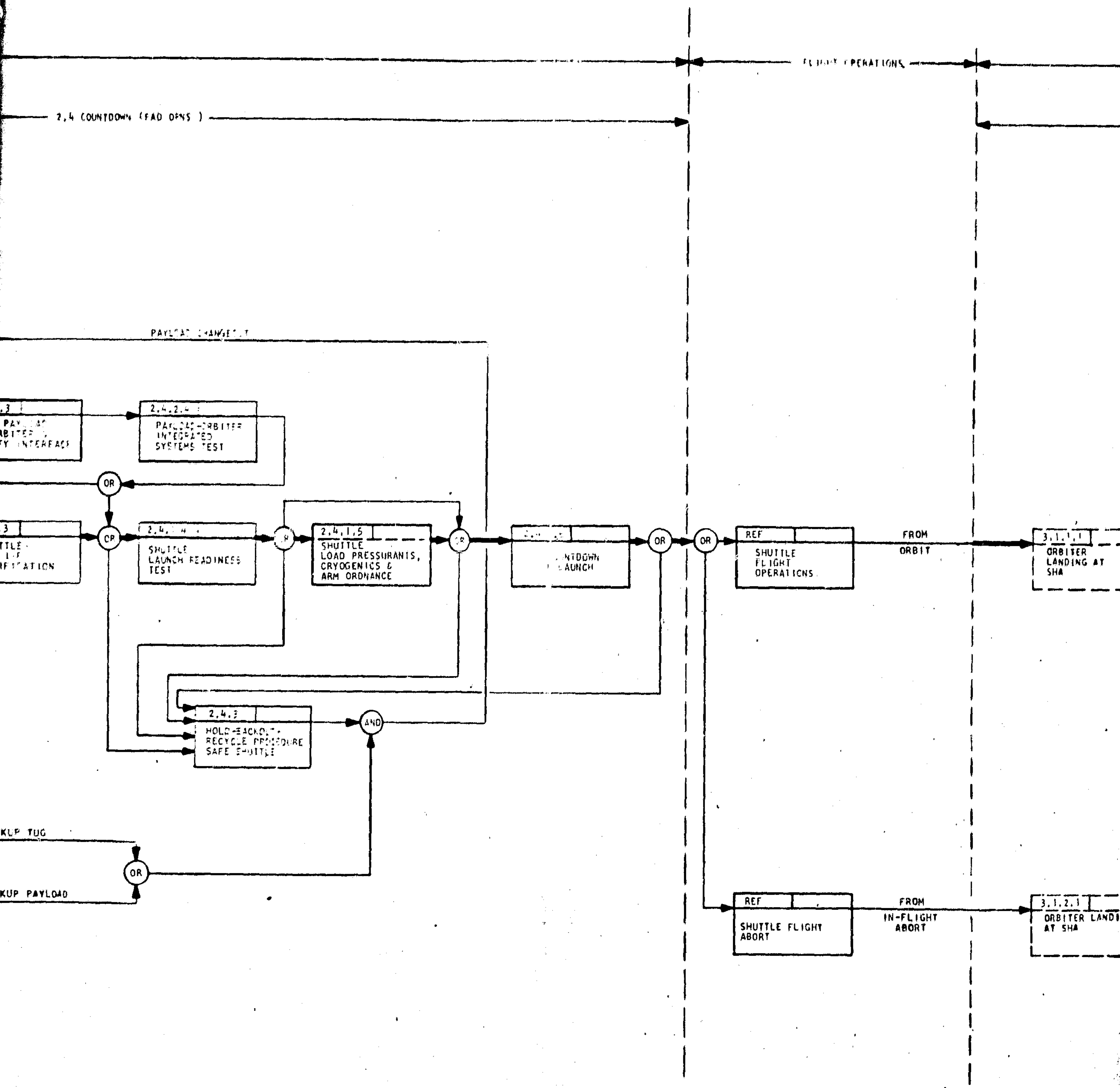

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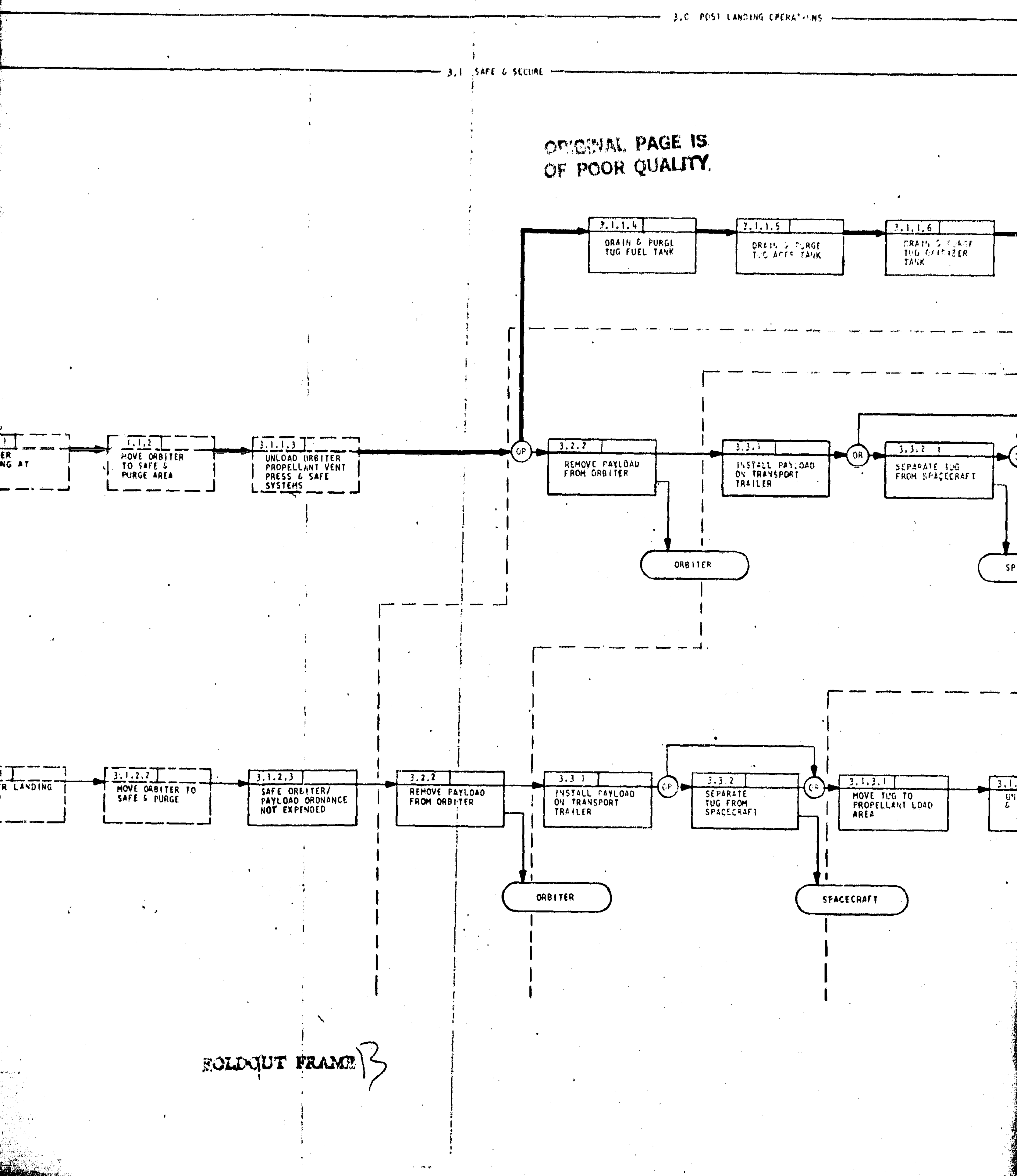

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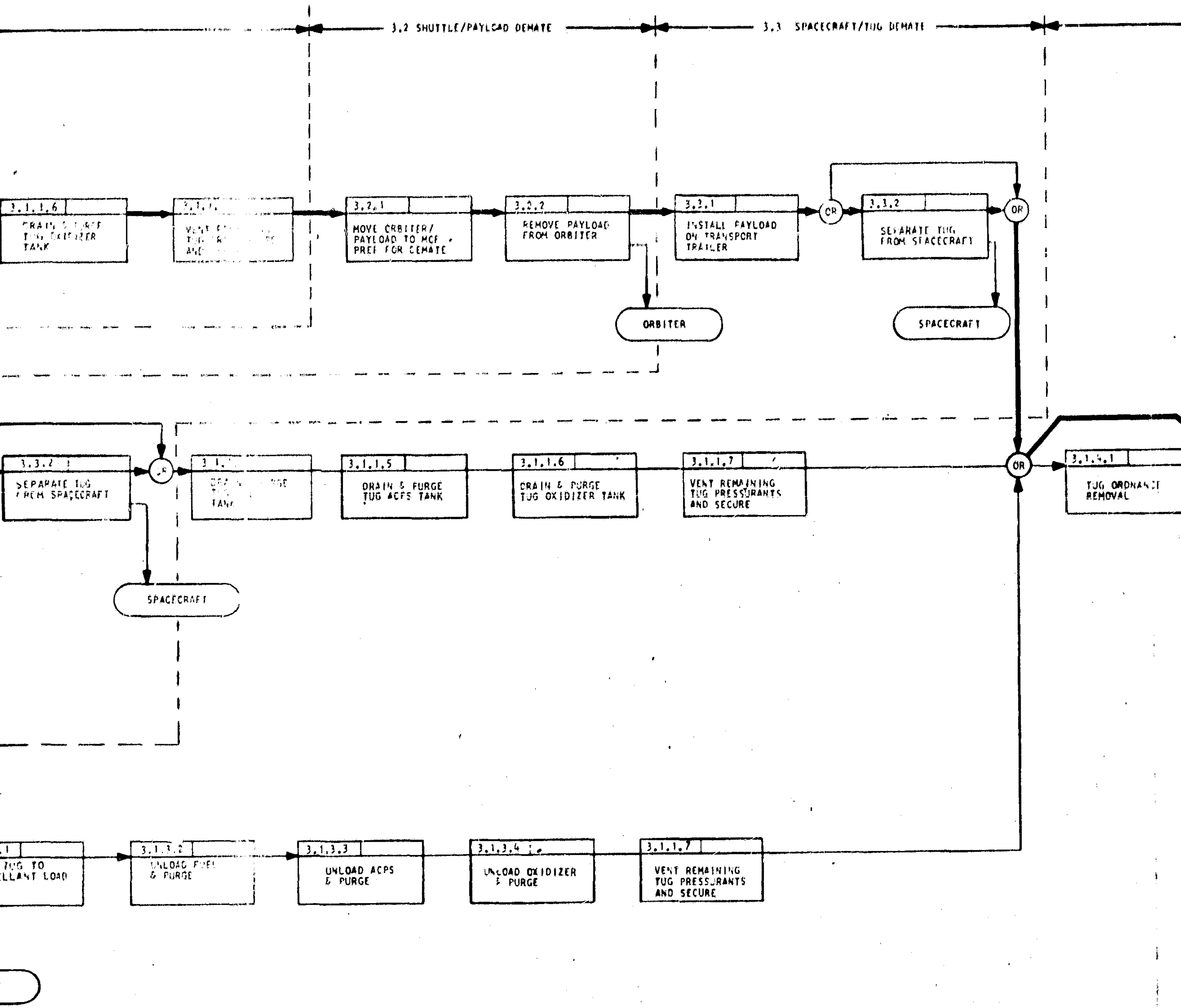

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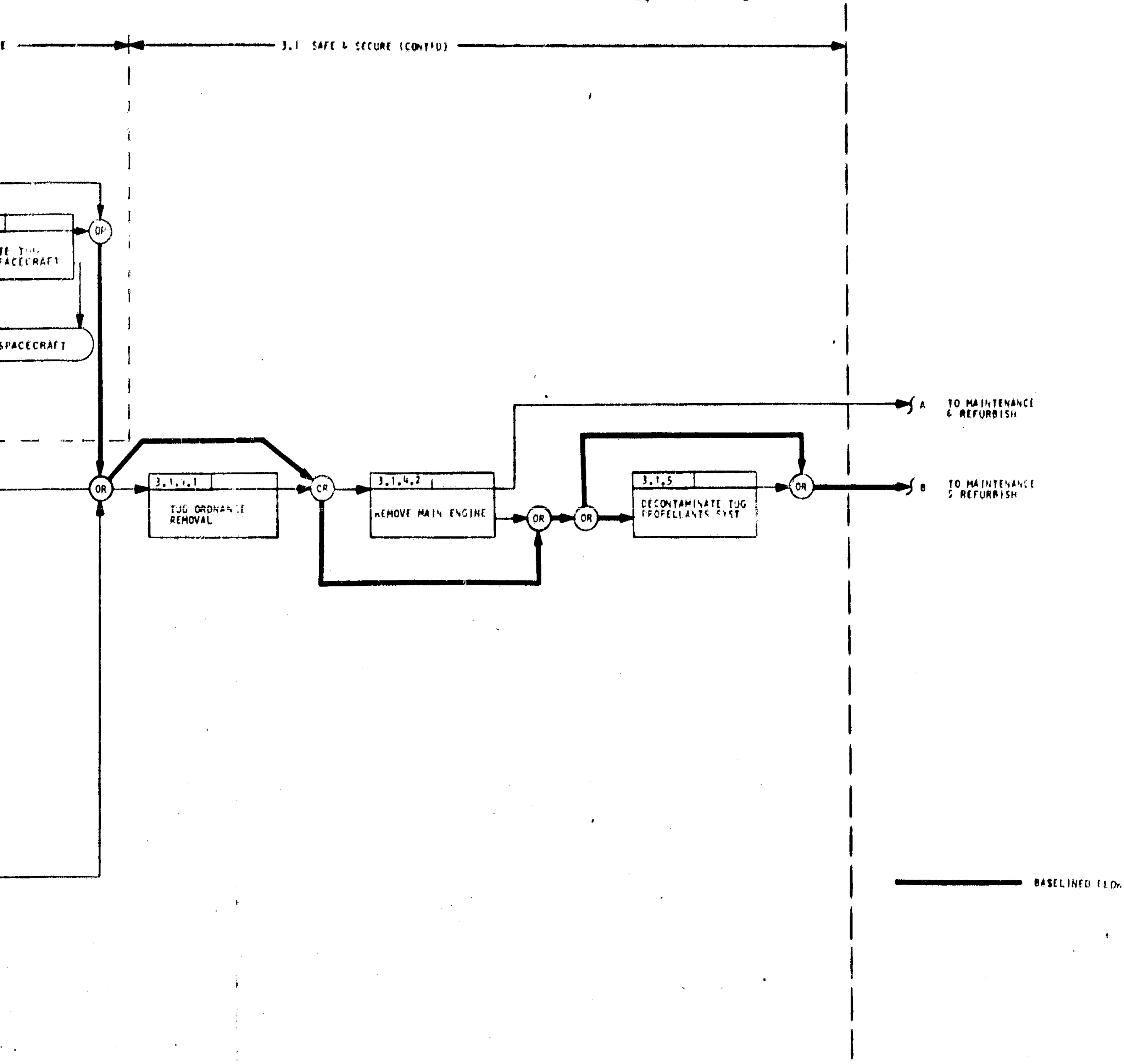

Fig. 2.5-3 Space Tug Launch-Site Ground-Operations Timelines

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2.5.2.5 Logistics - Logistics support provides the systems and disciplines required to ensure integrated logistics throughout the program. Existing logistics systems, computer programs, and data products that have been proved on launch vehicles, Skylab, and Viking programs will be used to support the Tug. The logistics technical approach defined is not sensitive to individual Tug configurations; however, costs associated with refurbishment, repair, spares, and transportation do vary, based on the design complexity of the different configurations, fleet size, and the number of Tug missions. Variations in costs of logistics support for the different Tug configurations are reflected in the logistics, refurbishment and integration sections of the WBS (320-05/13/14).

Elements included in the overall logistics program are maintenance analysis, spares selection/management, identification, development and conduct of the training program, and management of vendor documentation. Primary documentation to be prepared will be operations, maintenance, and handling manuals for the GSE, remove-and-replace procedures for Tug components, and transportation and handling plans for all program equipment.

Spares required to support the Tug program for each of the four configurations have been identified and are based on anticipated issue rate, repairability, lead time to procure or repair, quantity per Tug, and cost. Major factors in determining spares were the concepts that:

1) A repaired avionic component is considered to have zero operating time when it is put back in service.

2) Propellant pressurization and mechanical components can be refurbished a specific number of times and are considered to have zero operating time after refurbishment.

2.5.2.6 Facilities - Facilities required to support the Tug program can be grouped into two categories--ground test and launch operations.

Ground test facilities include all facilities and equipment necessary to build, assemble, and check out the Tug at the contractor's facility, and to perform required static and dynamic testing of the vehicle and its related subsystems. These facility requirements are listed in Table 2.5-7 by specific buildings and areas, extent of modification required, and general elements of work to be performed in each.

Facilities considered at launch sites are those required to service, maintain, launch, and recover the Tug. Also included at both areas are provisions for administration and logistics support. Table 2.5-8 itemizes the major buildings and areas required and the degree of modification anticipated to support the Tug program.

Table 2.5-7 Denver and Off-Site Facilities Plan

Facilities	Code	Purpose	Use D	Use Q	Use A
Martin Marietta Denver					
1. Engineering Materials Lab	1	Materials/comp test & verif	X	X	
2. Environmental Lab	1	Black box testing	X	X	
3. Structures Lab	1	Tank/structures (GVS) testing	X		
4. Leak Test Facility	1	Tank mass spectrometer He leak test	X	X	X
5. Space Simulation Lab	1	Thermal vacuum test		X	
6. Space Support Bldg Hi-Bay Assy	2	In-line-assembly tests	X	X	X
7. Space Support Bldg Accpt Test Fac	2	Acceptance testing	X	X	X
8. Controls Mock-Up Laboratory	2	Guidance systems test/verif	X	X	X
9. Cold Flow Laboratory	1	Propulsion sub & systems test	X	X	
10. Manufacturing	1, 3, 4	Tug & Tug struct component build	X	X	X
11. EMF	1	Electronic component build & C/O	X	X	X
12. Failure Analysis Lab	1	Analyze failures	X	X	X
13. Space Operations Simulator Lab	2	Docking simulation	X	X	X
14. Inertial Guidance Laboratory	2	Star tracker test & verif	X	X	
Off-Site Test Facilities					
1. White Sands Test Facility Engine Test Facility 401	1	Hot engine firing	X		
2. Johnson Space Center Chamber A	1	Thermal vacuum & solar testing (Final Option 3A only)	X	X	

Legend:

1 Existing facility—little or no mod required

2 Modify existing area/facility

3 New facility required for Final Option 3A only

4 Factory mod required for Final Option 3A only

D = Development testing

Q = Qualification testing

A = Acceptance testing

Table 2.5-8 KSC and WTR Facility Plan

Facilities	Code	Purpose	Use KSC	Use WTR
1. Maintenance & checkout facility (spacecraft processing facility)	3	Tug, checkout, spacecraft mate, storage maintenance & refurbishment, Class 100,000 cleanliness level	X	X
2. Propellant loading facility	2	Propellant & pressurants loading & final leak test	X	X
3. Safing area	1	Hanger for safing & deservicing before removal	X	X
4. Launch complex	1	Retractable clean room (Class 100,000) on launch tower plus overhead cranes for Tug removal & replacement	X	X
5. Ordnance storage facility	1	Handling & storage of kick-stage motors	X	
6. Orbiter mating facility	1	Tug-Orbiter mate & demate	X	X

Legend:

1 Existing facility required for Orbiter

2 Existing facility mod

3 New facility

2.5.2.7 Ground Support Equipment - GSE required to test and support the Tug program from design development through last launch is itemized in Table 2.5-9.

Table 2.5-9 Ground-Support Equipment Summary

GSE Type	End Items* Final Options				Total Units† Final Options			
	1	2	3	3A	1	2	3	3A
Electronics	18	21	21	22	53	88	91	94
Servicing	18	18	18	18	155	175	180	180
Handling	22	22	22	27	147	138	163	211

*Function of final option design

†Function of final option fleet size and/or launch rate

Electronic GSE makes maximum use of on-board functions for test and checkout of the Tug avionics subsystem, and of the three types of GSE, is most sensitive to Tug development. The design concept of electronic GSE has the flexibility for a phased growth to support projected mission growth of delivery and/or retrieval. The design concept also envisions a ground computer test set common to the launch processing system (LPS) for use during factory acceptance. This approach will permit generation of compatible software for both factory and launch sites.

Servicing GSE is totally Tug oriented. However, Tug servicing will be very similar to that for the OMS, and nearly identical to that for the Titan Transtage. As a result, a minimum of new design is required to have these items ready for production. When similar functions are being performed for the OMS, it is expected that identical GSE may be used with only an interface kit added for adaptation to the Tug. More detailed scheduling may point out common use of specific items that could result in program cost savings.

Handling GSE is completely new in design and will be built for the Tug because of the unique structural interfaces, interrelations between the Tug and the cradle, and Shuttle installation and removal requirements. The intent is to make handling GSE simple in design, functionally interrelated, and easily portable for maximum use of each item at all contractor and launch sites. Design and construction will stress simplicity and durability instead of complexity, light weight, and hence, higher cost.

2.5.2.8 Maintenance and Refurbishment - Maintenance and refurbishment concepts and requirements developed during the study provide effective and economical logistics support to meet turnaround and launch requirements for the Tug.

Scheduled (preventive) and unscheduled (repair) maintenance will be performed on the Tug and its ground support equipment in a manner consistent with the operational time constraint, to prevent deterioration of inherent design levels of reliability and operating safety and accomplish support and protection at a minimum practical cost.

Scheduled and unscheduled maintenance performed either directly on the Tug, associated ground support equipment, or in a supporting role will be categorized into the following levels: (1) first-level (organizational), (2) second-level (intermediate), and (3) third-level Maintenance (depot).

Refurbishment and repair (R&R) costs have been determined for all final option Tug configurations as well as for the kick stages. Information obtained from analysis of maintenance, subsystem design, fleet sizing, and total launches all entered into the final cost evaluation. Major drivers in computing program R&R costs are the quantity and types of components for each Tug configuration, the number of flights a Tug and component will experience, and projected failure rates.

Preliminary main-engine costs were received from Aerojet Liquid Rocket Company and are factored into WBS 320-13/14.

2.5.2.8.1 Refurbishment Approach - Refurbishment is performed on propellant pressurization and mechanical components according to their wear characteristics and the need to incorporate soft goods (O-rings and valve seats).

The frequency of required refurbishment was determined during the maintenance analysis. When the average number of flights (uses) exceeds the frequency of refurbishments, the component is replaced. The removed unit is then reworked and verified as a serviceable spare and placed in stock. If the frequency of refurbishments exceeds anticipated average flights per Tug, no refurbishment cost is included.

Analysis of avionics components resulted in the concept that current state-of-the-art units will not be refurbished on a time-limited basis. Instead, the condition of avionics will be monitored and components considered serviceable until on-board or ground checkouts determine otherwise.

2.5.2.8.2 Repair Approach - Repair (unscheduled maintenance) is required by failure of a component during flight (noncatastrophic) or ground checkout. Upon receipt of the component at third level maintenance, the unit is routed to the appropriate location for complete repair and reacceptance. Reacceptance constitutes functional verification and verification of "zero" time on the unit. It is then returned to stock as a spare.

Repair costs for each option were computed using standard issue rates as a basis for the number of probable failures throughout the program. It was also assumed that launch-to-launch flight cycle was one use for any specific component.

An assumption made in computing the total repair cost was that major repair would be made by the component supplier at his facility. This approach eliminated the indeterminable cost aspect of providing the suppliers' acceptance and repair capability at one or both launch sites. When subsystems are completely defined, a more detailed analysis of this approach should be made.

Repair costs for GSE are estimated to be a percentage of acquisition cost. Because much of the effort for GSE is in structural fabrication (chassis racks, frames, etc, as well as assembly and test), a realistic technique is to compute the percentage against only the procured items that historically have high repair costs. Therefore, repair costs for GSE in each option were set at 20% of acquisition cost for major procured items.

2.5.2.9 Manufacturing - Tug manufacturing concepts for the final options have been developed with concern for logical fabrication of subassemblies that flow parallel through production and converge at the final assembly and installation position. Basic manufacturing techniques and processes required to fabricate, inspect, and test the Tug have all been proved. Tug-peculiar configurations for composite fabrications and welding of the screen tension device will require supporting research and technology (SR&T) to optimize detail design and fabrication processes. Fusion and resistance welding techniques will be developed for material gages necessary for Tug tanks. Processes will first be qualified on the static test article, then optimized and validated on the first production vehicle. Although detailed analyses were conducted for each final option, it has not been determined that the characteristics of each option have any direct effect on manufacturing, tooling, facilities, processes, skills, or planning philosophy.

Our manufacturing plan divides the Tug into logical subassemblies that can be built and tested as separate units. The oxidizer and fuel tank sections and the vehicle forward shell are the three major components of the structure. The main propulsion and attitude control systems will be delivered to final assembly as

approximately 35 welded and tested subassemblies. Vehicle wiring will be built up on a tool and installed on the Tug as a complete harness. Figure 2.5-4 shows the flow of these major components through fabrication, assembly, installation, and test.

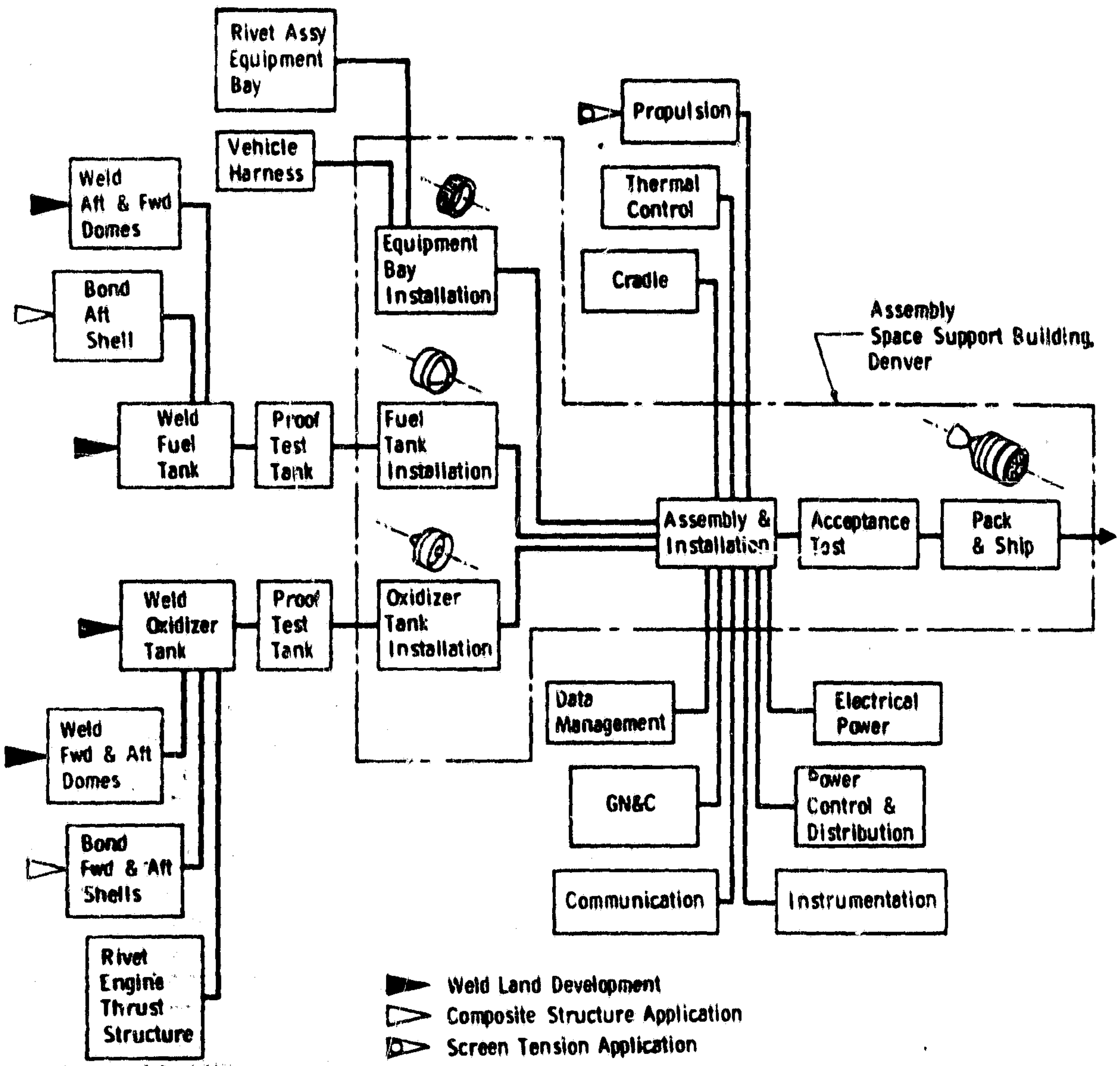


Fig. 2.5-4 Manufacturing Flow

2.5.3 Flight Operations

Flight and ground mission-support systems for the four Tug final options were examined to provide an overall operational analysis consistent with current levels of definition. A summary of this examination is presented in this section. Details are in Vol 6.0, Sect I of the *Selected Option Data Dump* (Ref 5.8).

2.5.3.1 Ground Rules And Assumptions - Tug flights will be conducted by both DOD and NASA as the prime operating agencies. For visibility and uniform understanding of the operations concepts of the two agencies, the following ground rules and assumptions were used.

- The USAF will be the executive agent and mission operating agency for the DOD and all DOD users; NASA will act in the same capacity for all users other than DOD.

- The Space Shuttle and Tug upper stage will be launched from both KSC and VAFB during the operational program. NASA will be the launch agency at KSC; USAF will be the launch agency at VAFB. Each agency will have missions requiring the use of both launch sites.

- NASA will provide all general-purpose Shuttle facilities at KSC; DOD will provide such facilities at VAFB. DOD payloads will be processed in a DOD-controlled facility at both VAFB and KSC.

- A DOD Shuttle system simulator will be at VAFB for training DOD personnel. This simulator will be available for closed-loop simulations with the VAFB launch control center (LCC), KSC LCC, and the Sunnyvale operations management center (OMC).

- Vehicle operations management control will be assumed by the operating agency at holddown release, regardless of the launch site.

- Operational management control of DOD missions will be exercised from a DOD OMC located with the STC at Sunnyvale and using the AFSCF network. Operational control of NASA missions will be exercised from a NASA operations center. The DOD may use NASA-developed software in its OMC. DOD-unique software, if required, will be developed and provided by the DOD.

- Each operating agency will be responsible for planning its own missions. Shuttle mission design and mission planning capabilities of both operating agencies will be compatible in crew training, procedures, contingency handling, and rescue mission design. Additionally, on-board software will be compatible in crew training, procedures, contingency handling, and rescue mission design. Additionally, on-board software will be compatible with launch and control centers and mission simulation facilities, and will be the same for all vehicles except for some mission-peculiar subroutines.

- NASA will maintain a common data base to be used for mission design and operations support by both operating agencies. The Tug contractor and launch centers will make appropriate performance and calibration data updates to the data base as required.

- Tug autonomy levels will be preempted, following Tug deployment from the Orbiter, for RF command and data flow verification, and during Tug recovery for statusing and safing.

- The use of an operations S-band tracking and data relay satellite system is assumed.

- The DOD and NASA will provide a joint, coordinated use of facilities for the resolution of contingency situations on the Shuttle.

2.5.3.2 <u>Orbital Operations Performance Data</u> - A general description of Tug configurations selected for each final option was presented in Table 2.4-1.

Design performance data (weights, propellant load sizing, velocity budgets, etc) required to define the capability of the selected Tug and kick-stage configurations evolved in this study are summarized in para 2.1. These were presented in detail in Vol 6.0, Sect. I of the *Selected Option Data Dump* (Ref 5.8).

These configurations have been shown to be capable of capturing all baseline missions defined by NASA and DOD, using the following flight modes:

- <u>Reusable Tug Modes</u> (delivery, retrieval, round trip) - generally the preferred techniques;

- <u>Kick Stage Modes</u> - Used only on the more difficult planetary missions;

- Delayed Retrieval Flight Mode - Used only on geostationary missions;

- Expendable Mode - Used only on the more difficult deep space missions.

In parallel with the evolution of design data, orbital-operations performance requirements were examined to assess the air/ground operational interface. Critical functions or mission events affecting crew safety and mission success were identified by mission phase and generalized for applicability to most mission profiles. When assessed with the operational modes defined by autonomy level, a ground/on-board interface functional responsibility matrix was developed (Table 2.5-10). The following definitions apply:

Prime - Normal planned functional responsibilities;

Auto - On-board computer control and limit check;

Backup - Requires ground decision that on-board system failed;

Override - On-board requests assistance from ground;

Shared - Functional responsibility divided between on-board and ground.

Autonomy Level II was used as a baseline for the final options presented in para 2.4. The definitions of all autonomy levels are listed below.

Level I Autonomy

- Completely independent of any man-made inputs after separation (beacons, orbiter, ground)

- On-board measurements and calculations allow mission to be completed in its entirety, including all Tug and spacecraft operations

- Final on-board rendezvous and docking capability

- Command uplink override capability and telemetry downlink

Table 2.5-10 Ground/On-board Functional Responsibility by Mission Phase

Mission Phase	Function	Autonomy Levels I & II On Board	I & II Ground	III On Board	III Ground	IV On Board	IV Ground
Mated Ascent	Contingency propellant dump for abort	Prime	Override	Prime	Backup	--	Prime
	Monitor Tug systems for out-of-limits conditions	Auto	Override	Shared	Shared	--	Prime
Orbiter Park	Tug system checkout in Orbiter bay	Auto	Override	Shared	Shared	--	Prime
	Orbiter/Tug fluid interface disconnect	Auto	Override	Prime	Backup	Prime	Backup
	Continue Tug systems verification deployed on RMS arm	Auto	Override	Shared	Shared	--	Prime
	Orbiter/Tug electrical interface disconnect	Auto	Override	Prime	Backup	Prime	Backup
	Complete systems verification after release of Tug	Auto	Override	Shared	Shared	--	Prime
	High-gain antenna deployment	Auto	Override	Prime	Backup	Prime	Backup
	Alignment check of IMU with orbiter & separation burn (ACPS)	Auto	Override	Prime	Backup	--	Prime
Pre-Main Engine Burn	IMU realignment using star tracker	Auto	Override	Prime	Backup	Prime	Backup
	Solar-array retraction*	Auto	Override	Prime	Backup	Prime	Backup
	Acquire burn attitude	Auto	Override	Prime	Backup	Shared	Shared
Main Engine Burns	Main engine preparation sequence	Auto	Override	Prime	Backup	Prime	Backup
	Main engine burn	Auto	Override	Prime	Backup	Shared	Shared
	Main engine shutdown sequence	Auto	Override	Prime	Backup	Prime	Backup
Post-Main Engine Burn (Coast)	Solar array deployment & articulation*	Auto	Override	Prime	Backup	Prime	Backup
	Acquire/hold thermal attitude	Auto	Override	Prime	Backup	Shared	Shared
	State vector updates	I-Auto II-Prime	Override Backup	Prime	Backup	--	Prime
Pre-S/C Delivery	Solar array retraction*	Auto	Override	Prime	Backup	Prime	Backup
	Acquire delivery attitude	Auto	Override	Prime	Backup	Shared	Shared
	Spin up spacecraft (if required)	Auto	Override	Prime	Backup	Shared	Shared
	Perform predelivery checkout of spacecraft*	Auto	Override	Prime	Backup	Shared	Shared
S/C Delivery	Electrical interface disconnect*	Auto	Override	Prime	Backup	Prime	Backup
	Release spacecraft	Auto	Override	Prime	Backup	Shared	Shared
Post-S/C Delivery	Solar array deployment & articulation*	Auto	Override	Prime	Backup	Prime	Backup
	Acquire thermal attitude	Auto	Override	Prime	Backup	Shared	Shared
	Stationkeep**	Auto	Override	Prime	Backup	Shared	Shared
Pre-S/C Pretrival**	Retract solar array	Auto	Override	Prime	Backup	Prime	Backup
	Acquire rendezvous attitude	Auto	Override	Prime	Backup	Shared	Shared
S/C Retrieval**	Rendezvous with spacecraft	Auto	Override	Prime	Backup	Shared	Shared
	Acquire docking attitude	Auto	Override	--	Prime	--	Prime
	Spin-up docking adapter, if spacecraft is spinning	Auto	Override	--	Prime	--	Prime
	Dock	Auto	Override	--	Prime	--	Prime
	Despin, if required	Auto	Override	Prime	Backup	Prime	Backup
Post-S/C Retrieval**	Acquire deorbit attitude	Auto	Override	Prime	Backup	Shared	Shared
Pre-Orbiter Rendezvous	Establish Tug/Orbiter RF link	Prime	Backup	Prime	Backup	Shared	Shared
	Safing/passivation	Prime	Backup	Prime	Backup	--	Prime
	***Solar array & high-gain antenna retraction	Auto	Override	Prime	Backup	Prime	Backup
Orbiter Retrieve on RMS	Reestablish electrical interface	Auto	Override	Prime	Backup	Prime	Backup
	Perform exhaustive systems limit checks/verification	Prime	Backup	Shared	Shared	--	Prime
Post-Retrieve in Orbiter Bay	Reestablish fluid interfaces	Prime	Backup	Prime	Backup	Prime	Backup
	Systems status report to ground to expedite turnaround	Prime	Backup	Prime	Backup	Prime	Backup

*Does not apply to Final Option 1
**Does not apply to delivery-only cases
***Solar Array Retraction not applicable to Final Option 1

Level II Autonomy

- Ground or navigation satellite beacons acceptable (either must serve multiple users)

- Level I autonomy required for orbits in which ground or satellite beacons do not provide satisfactory state determinations

- Final on-board rendezvous and docking capability

- Command uplink override capability including spacecraft status. redirection and retargeting of mission with telemetry downlink

Level III Autonomy

- Ground stations provide state update during entire mission

- On-board calculations are performed for mission completion

- Final rendezvous is made by on-board capability

- Final docking with ground support

- Command and telemetry capability

Level IV Autonomy

- All phases are controlled from the ground

- Calculations are performed primarily on the ground (such as main burn and midcourse—duration and direction)

- Ground will control final rendezvous and docking

- Command and telemetry capability

2.5.3.3 Network/Communication - Ground-station passes and contact times required to maintain readiness for ground command override during critical Tug functions were developed using representative mission timelines. These data are summarized in Table 2.5-11. Details are presented in Vol 6.0, Sect. I of the *Selected Option Data Dump* (Ref 5.8). Station passes and contact times are shown as requirements and were not compared with ground-station coverage. Therefore, contact times are independent of the network used and there may be some incompatibilities (i.e., a requirement to communicate with the Tug for monitoring and/or command override during critical events when there is no ground station coverage).

Due to ground-station pass-duration variations with altitude, any requirements for contact times in excess of 10 minutes were divided into two passes if altitude was less than 5000 km, but listed as one pass if more than 5000 km. Minimum monitoring time shown for any event is one minute, to allow for data lock-on and analysis in case override commands are required.

An operational S-band tracking and data relay satellite (TDRS) system was assumed; however, there are known ground-station constraints above 5000 and below 1300 km because of incomplete coverage. They are not reflected in this study.

Mission-critical functions requiring ground override action could conceivably occur in any mission phase or any autonomy mode; hence, network readiness and manning-level requirements are not expected to vary greatly with mission phase or with the first three levels of autonomy.

2.5.3.4 Guidance and Navigation - The purpose of the guidance and navigation error analysis portion of the Tug study was to ensure that the subsystems selected allow the Tug to meet the specified delivery accuracy requirements and return to the Orbiter within accuracy uncertainties that permit the Orbiter to acquire and rendezvous with the Tug. Further, requirements for midcourse corrections and/or vernier burns to meet these accuracies were defined for impact on subsystem design. Various types of navigation systems were analyzed to determine their ability to meet the different autonomy levels. Navigation with periodic updates from ground tracking stations was evaluated as a system meeting the Autonomy Level III requirements. One-way doppler (OWD) and interferometer landmark tracking (ILT) systems were considered for Autonomy Level II, and horizon sensors (HS) were considered as the only satisfactory candidate meeting the requirements of Autonomy Level I.

Table 2.6-12 Tug Network Operations Requirements

Mission	Station Config	Category	Tug Mode 1	2	3	4	5	6
Geostationary	15 Stations	No passes below 5000 km	13	15	15	15	12	15
		Total contact time (min)	86'	104	104	116	98	84
	TDRS + 5 Stations	No passes above 5000 km	3	5	6	3	4	3
		Total contact time (min)	86	104	116	116	98	84
High-Inclination Circular/ Elliptical*	15 Stations	No passes below 5000 km	13	15	15	15	12	15
		Total Contract Time (min)	86/72	104/90	116/102	116/102	98/84	84
	TDRS + 5 Stations	No passes above 5000 km	3/2	4/3	4/3	3/2	4/3	3
		Total contact time (min)	86/72	104/90	116/102	110/102	98/84	84
Outer Planetary*	15 Stations	No passes below 5000 km	13			14		
		Total contact time (min)	62			102		
	TDRS + 5 Stations	No passes above 5000 km	1			2		
		Total contact time (min)	62			102		

Note: Level II autonomy assumed

* Extrapolations of analyzed cases because computer runs performed on geostationary mission only

Tug Mode 1 = Single-stage deliver only - Final Option 1 Tug
Tug Mode 2 = Single-stage delivery/retrieval - Final Option 2 Tug
Tug Mode 3 = Delivery/retrieval (phase-developed) - Final Option 3 Tug
Tug Mode 4 = Stage-and-a-half delivery - Final Option 3A Tug
Tug Mode 5 = Delivery & first-half delayed retrieval } Special Cases
Tug Mode 6 = Second-half delayed retrieval } Special Cases

The predominant Tug mission objective was to deliver and/or retrieve a spacecraft from a geostationary Earth orbit. This type of mission demonstrates most of the complex vehicle functions and was therefore used as a basis for these analyses. Delivery accuracy requirements were specified for a geostationary mission, which allows a direct evaluation of results.

2.5.3.4.1 Ground-Update Navigation - Autonomy Level III allows a state update to be received from ground tracking stations during the entire mission. The ground network used in this analysis has 15 stations, as defined in Table 10-1 in Vol 6.0, Sect. I of the *Selected Option Data Dump* (Ref 5.8).

While continuous ground contact is not required to navigate successfully, a TDRS system has been assumed to be available that would permit receiving an update when the Tug was not within view of any of the 15 ground stations. Navigation uncertainty for a geostationary delivery mission to 87°E longitude was evaluated using a Martin Marietta computer program.

A discussion of the computer programs and derived navigational uncertainty results were graphically presented with supporting text in Vol 6.0, Sect. I of the *Selected Option Data Dump* (Ref 5.8). Accuracies for both the delivery and return-to-Orbiter states were within the requirements.

2.5.3.4.2 Autonomous Navigation - Autonomy Level I and II navigation requires a means by which the Tug can determine its attitude and state with on-board sensors and computational software, independent of any dedicated ground-generated information. Autonomy Level I further requires that no man-generated ground information (such as beacons) may be used. Three sensors meeting these autonomy requirements were considered for use with the on-board IMU package. A horizon sensor (HS) meets Autonomy Level I requirements and will provide a complete, although somewhat rough, estimate of the Tug's position above the Earth if the vehicle's inertial attitude is known from the IMU package. The HS model errors are assumed to originate from the altitude uncertainty of the CO_2 absorption layer and uncertainty in sensor Measurements.

An interferometer landmark tracker (ILT) and a one-way Doppler (OWD) system were investigated as candidates to improve the navigation capability of the HS and still meet Autonomy Level II requirements. The ILT is a phase detector that measures the phase difference between components of a wavefront received on two spatially separated antennas. Because it is capable of processing a short radar pulse, system performance is not degraded by rapid axial motion of the Tug.

The OWD system is "one-half" of the conventional Doppler process. OWD does not retransmit a signal, but compares the received frequency with the previously defined nominal frequency to determine relative velocity. Thus, the uncertainty (or instability) of the frequency source contributes to total sensor uncertainty, which is primarily a result of the precision of the on-board clock.

Error analyses for these sensor models were conducted using the same computer process used for ground-update navigation. The results were reported in Vol 6.0, Sect. I of the *Selected Option Data Dump* (Ref 5.8). Again, accuracies for both the delivery and return-to-Orbiter state were within requirements.

2.5.3.5 <u>Rendezvous and Docking</u> - The avionics rendezvous and docking requirement is met by addition of a scanning laser radar and video subsystem in the spacecraft interface rendezvous and docking module. The ACPS tanks are selected to provide the energy required to execute the rendezvous maneuver. Detailed avionics and propulsion considerations for specific options were presented in Vol 5.0, Sect. I of the *Selected Option Data Dump* (Ref 5.8).

A typical rendezvous sequence, shown in Fig. 2.5-5, consists of an initial (intercept) burn that places the Tug in a new orbit designed to intercept the target at a specified time. During the subsequent coast, guidance equations are resolved to determine if correction burns are required to ensure an interception. Then, a braking burn is executed to orbit with the target vehicle. Finally, another check is made to ensure that relative velocities are within hand-over requirements of the terminal system. Additional data showing a typical geostationary mission were presented in Fig. 11-2 and 11-3 of Vol 6.0, Sect. I of the *Selected Option Data Dump* (Ref 5.8).

1. Tug performs intercept burn at time T_1. (in this case, based on relative range & range rate data)

1'. Target position at T_1.

2. Check made to see if correction burn greater than an input tolerance (1 ft/sec) (0.305 m/sec) is required; burn executed if required

2',2". etc. Above check repeated at requested time intervals (200-sec intervals)

3. Braking burn performed at nominal distance behind target by Tug to orbit with target.

4. Check made to assure relative ΔV within specified tolerance (0.05 ft/sec)(0.015 m/sec).

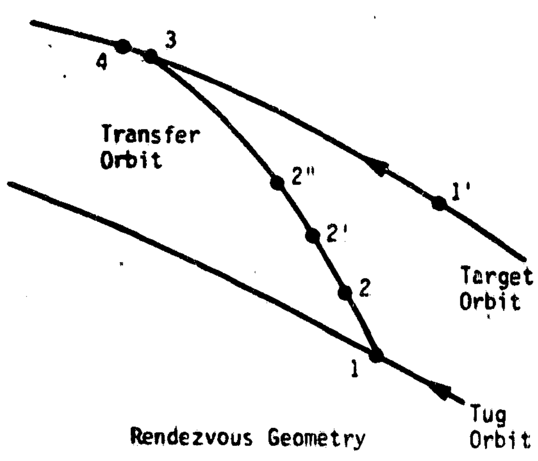


Fig. 2.5-5 Tug Rendezvous Sequence

From a range of approximately 30 n mi (55.6 km), the scanning laser radar, a ranging device baselined for Final Options 2 and 3, will track to a corner reflector on the target vehicle. From a range of approximately 100 ft (30.5 m) to dock and latch, a TV camera will be employed, using either, remote manual operation from the ground or an automatic data processing of light-bar-type data to satisfy automatic docking requirements. Laboratory evaluation using the ground operator concept was reported in Vol 5.0, Appendix D of the *Selected Option Data Dump* (Ref 5.8).

Rendezvous and docking may be feasible without using a separate video camera. Its absence would impose a severe operational limitation because backup or workaround capability would be minimal if the initial docking attempt failed. A video camera will permit manual intervention, and is a significant requirement for operational flexibility.

2.5.3.6 Software - Development and mission-peculiar updating of the Tug airborne computer software package is one of the major operations-oriented tasks in the Tug DDT&E program. Basically, the approach followed is similar to that used for the Titan IIIC system. The package will be capable of directing Tug over a defined range of mission possibilities; scientific equations are developed, and computer logic is programmed for this defined mission range.

The Tug flight software problem is more complex than that for conventional expendable deliveries like Titan IIIC. This greater complexity is shown by the use of a 4-megabit memory and three central processing units in the airborne computer, and it implies a more complex problem in software programming and validation. A conservative, completely redundant dual-validation loop is considered an absolute requirement for Tug system development.

The first loop employs an interpretive computer simulation (ICS). This validation provides a necessary development tool for diagnosis and validation of flight software. The ICS provides a complete digital simulation of the six-degree-of-freedom vehicle mechanics, servo response of the vehicle flight-control systems, and the airborne flight computer. In addition, a complete set of airborne computer diagnostics that permit tracing any anomalies in the flight program is provided.

The second validation loop uses a controls mockup (CMU) in which as many articles of flight hardware as possible (inertial measurement unit, flight computer, engine actuators, etc) are coupled with a hybrid computer simulation of those elements that cannot

be set up in the laboratory (flight mechanics, engine thrust, etc) The merit of the laboratory validation is that it provides maximum confidence in the software package that can be obtained short of actual flight test.

Playing the flight software through a flight computer in these facilities provides complete functional confidence in the system developed. Run times are real time (whereas ICS is slower than real time), and it is possible to validate all critical cases in the defined mission range. ICS validation, due to computational time and cost, can only sample critical cases. For rendezvous missions, the space operations simulation (SOS) containing a moving-base docking unit is routine as part of the CMU.

This dual (ICS/CMU-SOS) validation loop provides complimentary, complete confidence in the flight software package. After this validation, there is complete confidence that a software system capable of operating over the defined mission range has been developed. Then, the only recurring activity required to fly a particular mission within the scope of the defined mission range is preparation of specific mission targeting parameters, preparation of a mission-peculiar input tape, and verification that the tape has been prepared and entered in the flight computer as intended.

2.5.3.6.1 Spacecraft Deployment Software - The functional capability required of the flight software package to deliver spacecraft over the range of missions defined by NASA and DOD, and return to the Orbiter, is shown in Table 2.5-12.

The following assumptions were made relative to software development:

- SRT activity will be pursued diligently before the start of Phase C, and basic technology required to perform functions will be well in hand.

- Phase B will provide for trade studies that will identify what basic types of logic technique are to be used (e.g., what type of powered-flight guidance equations are best, whether the computer will use floating-point arithmetic, whether one-way Doppler will be used).

- Flight software will be capable of Autonomy Level I or II operation, with backup by ground system on demand or request.

Table 2.5-12 Delivery Capability On-Board Computer Functions

Guidance & Navigation

- Store Ephemeris Data, Etc
  - Mission Orbit
  - Shuttle Orbit
  - Ground Station Data (Trackers & Navigation Sources)
    - Physical Location
    - Electronic Characteristics
    - Availability Schedules
- Orbit Determination Logic
  - Using Inputs from IMU, Clock, Star Tracker & 1-Way Doppler (Horizon Scanner for Level I Autonomy)
  - On-Board Determination of Navigation Update
- Provide Powered Flight Guidance
  - Based on Updated IMU Navigation & Mission Targets

Flight Control

- Provide Required Stability & Transient Response during Powered & Coast Flight
- Control Pointing of Antennae & Solar Arrays

Malfunction

- Monitor Equipment Status & Take Corrective Action
- Manage Redundant ACPS Status & Backup Modes
- Perform Redundant Sensor Analysis, Computations & Discard Questionable Data

Data Management

- Manage System Data Flow over Data Bus
- Control Multiple CPU Memory as Function of Flight Mode
- Interface as Required with Ground Command, Data Link Systems

Ground Checkout

- Provide Data/Function Interface with Ground & Orbiter Computers
- Conduct On-Board Statusing in Conjunction with Ground, Orbiter Computers & Launch/Flight Crew Monitor or Override

- Maximum use of the flight computer for prelaunch check and in-flight self-check will be achieved.

- A complete dual validation of flight software will be made before first flight, through laboratory setup with maximum use of flight hardware (CMU) and complete simulation validation (ICS).

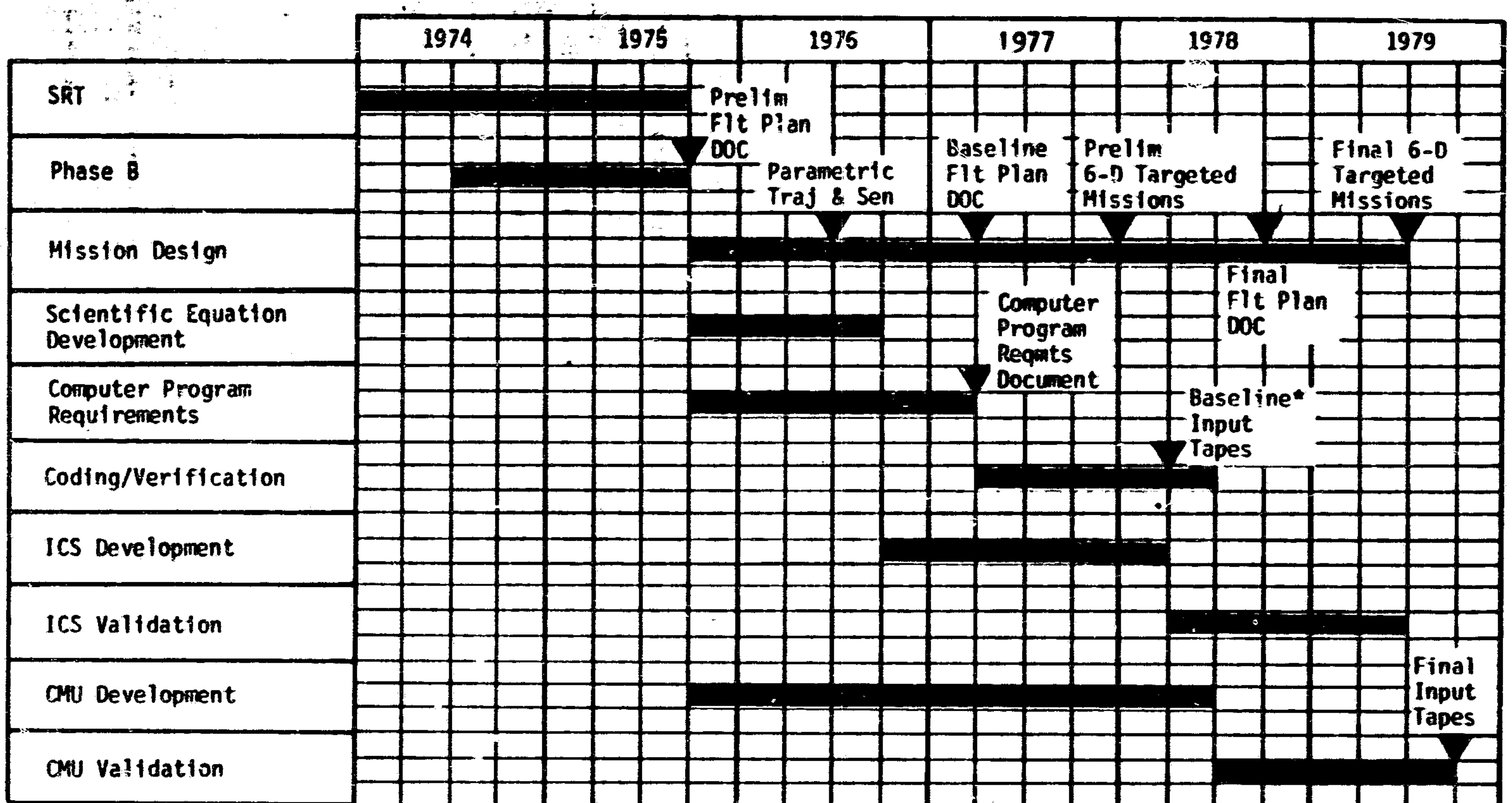
- Maximum flexibility of flight software to minimize recurring analysis required for mission-to-mission retargeting will be a goal.

- DDT&E will result in efficient computer tools to permit minimum analyst-in-loop activity in retargeting missions.

- There will be no CMU/ICS validation of a recurring mission.

Flight software development tasks and the schedule are shown in Fig. 2.5-6. A detailed discussion of these tasks is in Vol 6.0, Sect. I of the *Selected Option Data Dump* (Ref 5.8).

2.5.3.6.2 Computer Differences for Spacecraft Retrieval Capability - Retrieval capability requires the use of several additional components on the Tug and significantly more complex mission plans. Component additions include a rendezvous radar, TV docking camera, and mechanical docking mechanisms. Complications in mission planning include multiple-impulse to approach the



*Input functions are: Coded Program
G&N Targeting Parameters
Flight-Control Parameters

Fig. 2.5-6 On-Board Software Development Schedule

target, translational maneuvers to dock with it, and longer total mission durations to accommodate rendezvous sequences. These functional requirements require more on-board computer functions to direct the added activities.

Additional computer functions are summarized in Table 2.5-13.

Table 2.5-13 Additional On-Board Computer Functions for Retrieval Capability

<u>Guidance and Navigation</u> RADAR Use Algorithm TV Image Interpretation Algorithm Rendezvous Guidance Logic Docking Guidance Logic
<u>Flight Controls</u> ACPS Use for 3-Axis Translation Transient Response during Docking (Possibly Spinning S/C)
<u>Plus</u> Malfunction Detection, Data Management & Checkout for Added Components & Functions

The additional functions have an impact on the tasks shown in Fig. 2.5-6. A detailed discussion of this task impact was reported in Vol 6.0, Sect. I of the *Selected Option Data Dump* (Ref 5.8).

2.5.4 Orbiter Interfaces - Figure 2.5-7 shows the general arrangement and physical interfaces of the Orbiter and Tug. The specific interfaces (structural, avionics, fluid, operations, environmental including GSE, spacecraft), and design effects of the Tug on the Orbiter and spacecraft, are discussed in the following paragraphs. The discussions are typical for all Tug final options unless otherwise noted. Additional details are in Vol 5.0 of the *Selected Option Data Dump* (Ref 5.8).

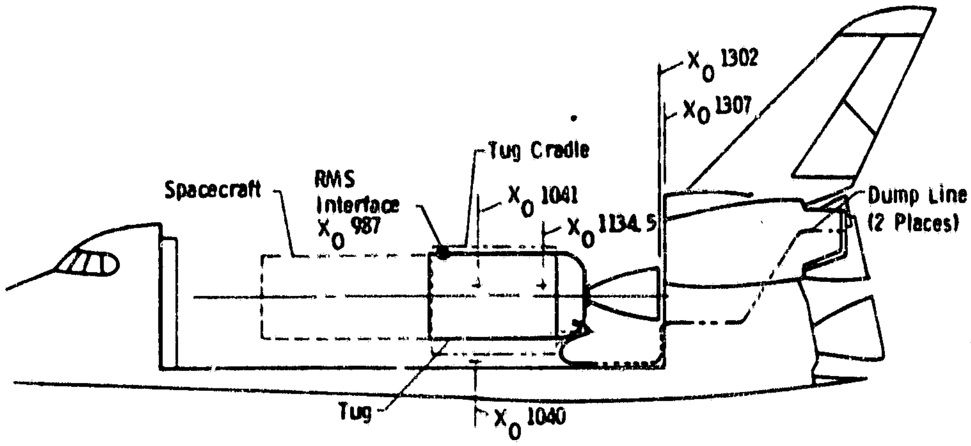


Fig. 2.5-7 General Arrangement

2.5.4.1 Orbiter/Tug Structural Interfaces

2.5.4.1.1 Tug Effects on Orbiter - One condition--an Orbiter abort landing with a fully loaded Tug [65,000 lb (29,484 kg)]--exceeds the allowable cradle/Orbiter support point interface load. These support points will require modification to accept the loads imposed by the Tug under this condition. (See Fig. 2.5-8 and -9.)

2.5.4.1.2 Tug-Provided Equipment and Interface Status

a. *Final Options 1, 2, and 3 Cradle* - Figure 2.5-8 shows the cradle design used for single-stage options. Cradle-to-Orbiter interface points are statically determinant, as defined in Fig. 2.5-9, with two vertical and two longitudinal cradle reactions taken at Orbiter Sta 1041, one vertical reaction at Sta 1134.5, and one lateral taken at Sta 1040. The Tug-to-cradle structural tie arrangement is statically indeterminant with eight lateral (Y) and eight vertical (Z) ties, and a vee-groove clamp for longitudinal loads (X).

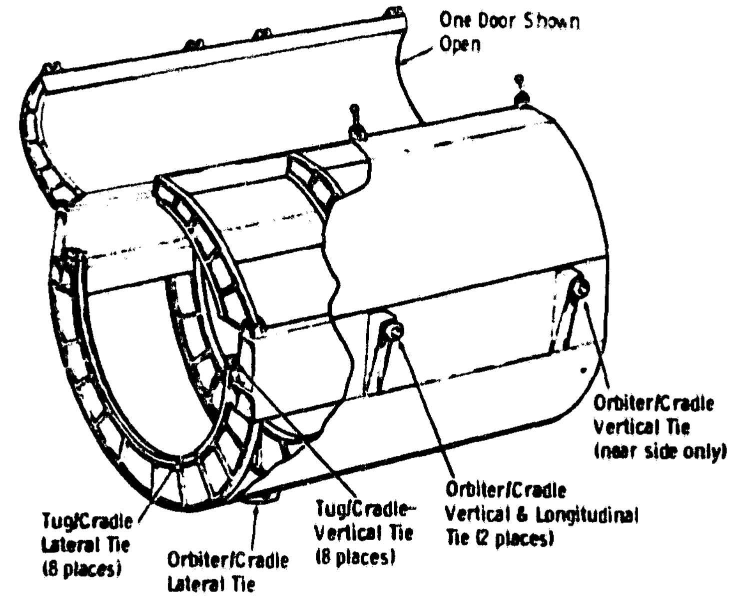
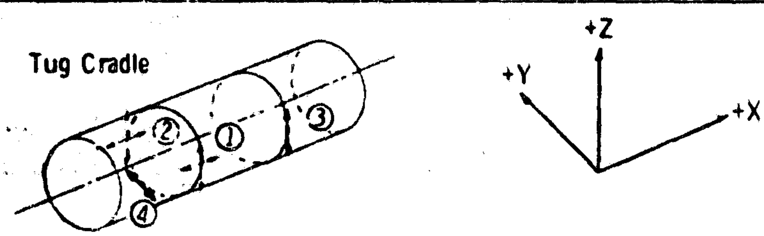


Fig. 2.5-8 Final Option 1, 2, and 3 Cradle Concept

Point	Coordinates			Allowable Loads Pounds (kg)			Maximum Tug Loads Pounds (kg)		
	X_0	Y_0	Z_0	P_X	P_Y	P_Z	P_X	P_Y	P_Z
1	1041	-95.5	414	±253,000 (±114,759)	0	±90,000 (±40,823)	+86,199 (+39,099) -146,543 (-66,471)	0 0	+ 97,494 (+44,223) - 59,364 (-26,927)
2	1041	+95.5	414	±253,000 (±114,759)	0	±90,000 (±40,823)	+90,024 (+40,834) -146,121 (-66,279)	0 0	+171,566 (+77,821) - 22,906 (-10,390)
3	1134.5	-95.5	414	0	0	±90,000 (±40,823)	0 0	0 0	+104,798 (+47,536) - 59,950 (-27,193)
4	1040	0	307	0	±109,000 (±49,442)	0	0	±130,229 (±59,071)	0



Note: Loads underlined exceed orbiter allowables and are for an abort case fully loaded.

Fig. 2.5-9 Single-Stage Tug/Orbiter Interface Loads

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b. *Final Option 3A Cradle* - Figure 2.5-10 shows the cradle design used for stage-and-a-half vehicles.

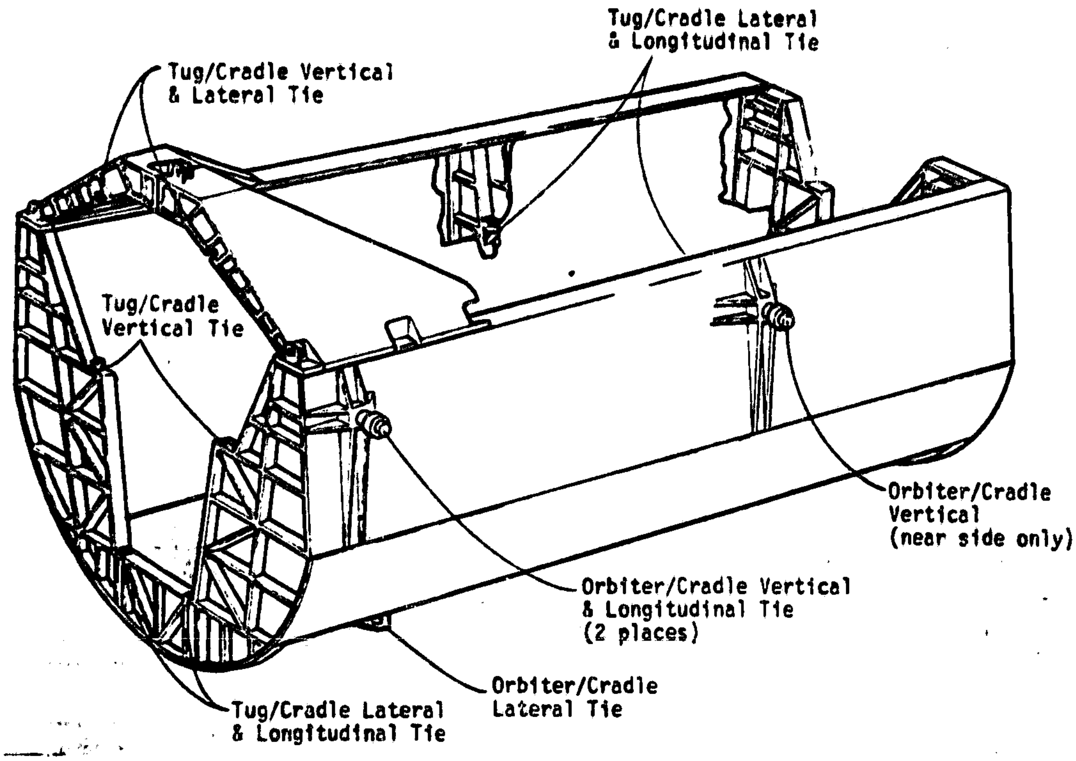


Fig. 2.5-10 Final Option 3A Cradle Concept

The cradle-to-Orbiter interface points are statically determinant as defined in *Payload Accommodations* (Ref 5.13). There are two fittings on the side box beams at the forward bulkhead that take longidudinal (X) and vertical (Z) loads into the Orbiter at Sta 1041. The third vertical (Z) tie is on the left box beam at Orbiter Sta 1181. The lateral (Y) load is taken out at a fitting on the forward bulkhead frame at Orbiter Sta 1040.

There are eight cradle-to-Tug interface points forming an indeterminant tie between cradle and Tug. Six of the eight tie points fall on the forward cradle frame. Two vertical (Z) Tug reactions are taken at cradle fittings on the side centerline at inboard flange areas. Two lateral (Y) and two longitudinal (X) Tug reactions are carried in the upper clamshell region and two other lateral and longitudinal reactions are carried in the lower fixed portion of the bulkhead frame. Fittings on the inboard sides of the box beams carry both vertical (Z) and lateral (Y) Tug reactions.

c. Center of Gravity - Each Tug configuration's cg falls within the Orbiter's requirements. Figures 2.5-11 and 2.5-12 show the longitudinal and vertical center of gravity for single-stage configurations (stage-and-a-half configurations are similar). Lateral cgs fall within 0.75 in. (1.91 cm) of the payload-bay centerline for all configurations.

d. Interface Loads - Each Tug configuration's interface load falls within the Orbiter's capability, except in the fully loaded abort case, as shown in Fig. 2.5-9.

2.5.4.2 Orbiter/Tug Avionics Interfaces

2.5.4.2.1 Tug Effects on Orbiter

a. Electrical - A relay contact is provided in the Tug return wiring (Fig. 2.5-13) to allow connection of the Tug return line to its vehicle ground point whenever the Orbiter return is not tied to its structure. The Orbiter should provide ability to control this relay.

Two redundant Orbiter electrical connectors that mate with the Tug connectors should have the size and number of wires shown in Fig. 2.5-14.

Tug power requirements are within the provisions of *Payload Accommodations* (Ref 5.13).

b. Data Management - One interface box, Orbiter- or Tug-provided, is required to interface the Tug data management subsystem and Orbiter data processing subsystem (computers). The principle circuits are:

1) Standard branch circuits to perform the Tug control-line time-division demultiplex and data-line multiplex functions;

2) Buffer registers for temporary word storage to accommodate differing dock rates and formats for data flowing in either direction;

3) A frequency divider (integrated circuits) to convert an Orbiter-supplied stable clock to the 2 MHz needed for Tug flexible signal interface (FSI) control (for Orbiter override capability);

4) A binary counter and sufficient AND logic to gate the buffer registers in a time-division multiplex manner for two-way FSI control (again needed for Orbiter override capability).

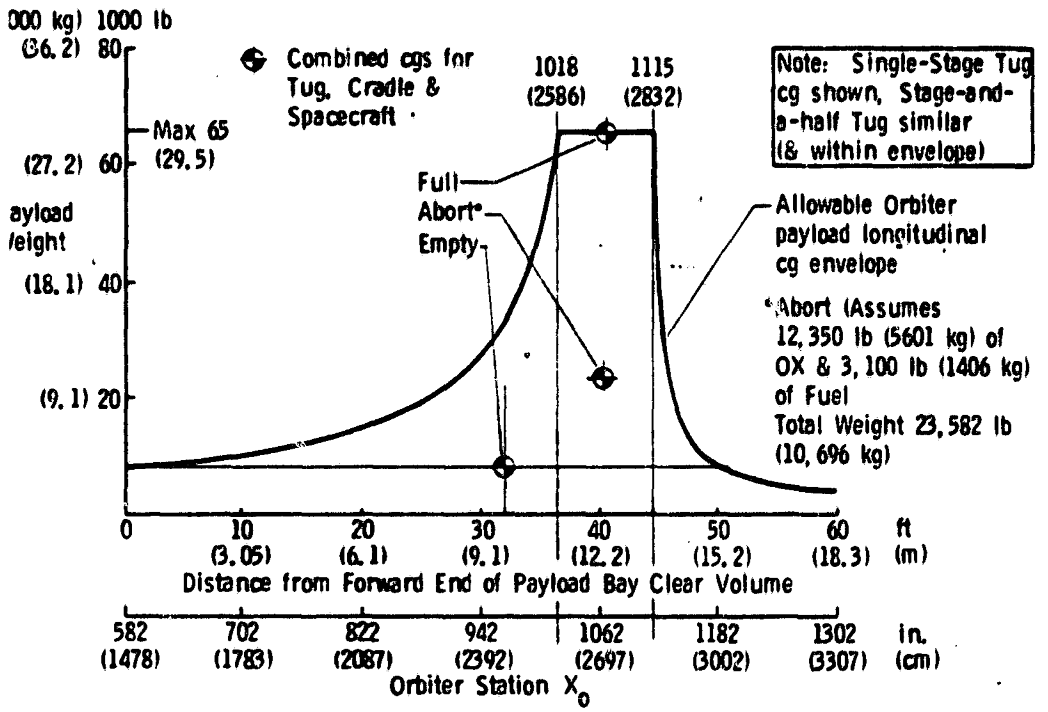


Fig. 2.5-11 Longitudinal Center of Gravity vs Allowable Envelope

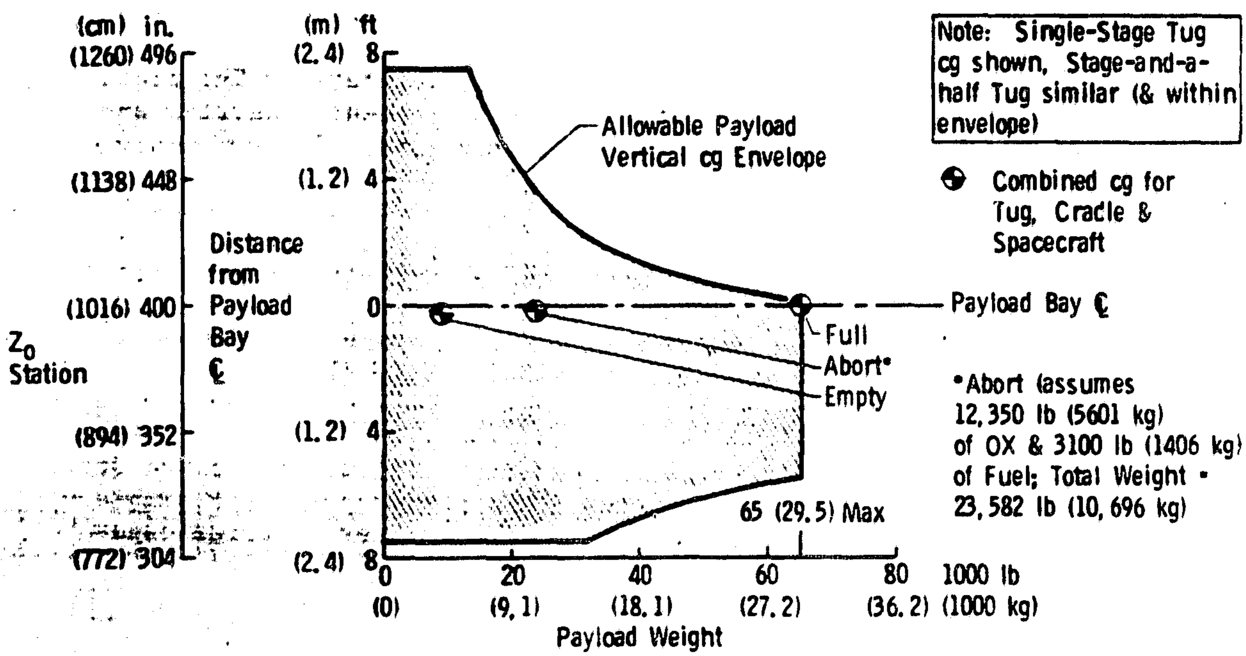


Fig. 2.5-12 Vertical Center of Gravity vs Allowable Envelope

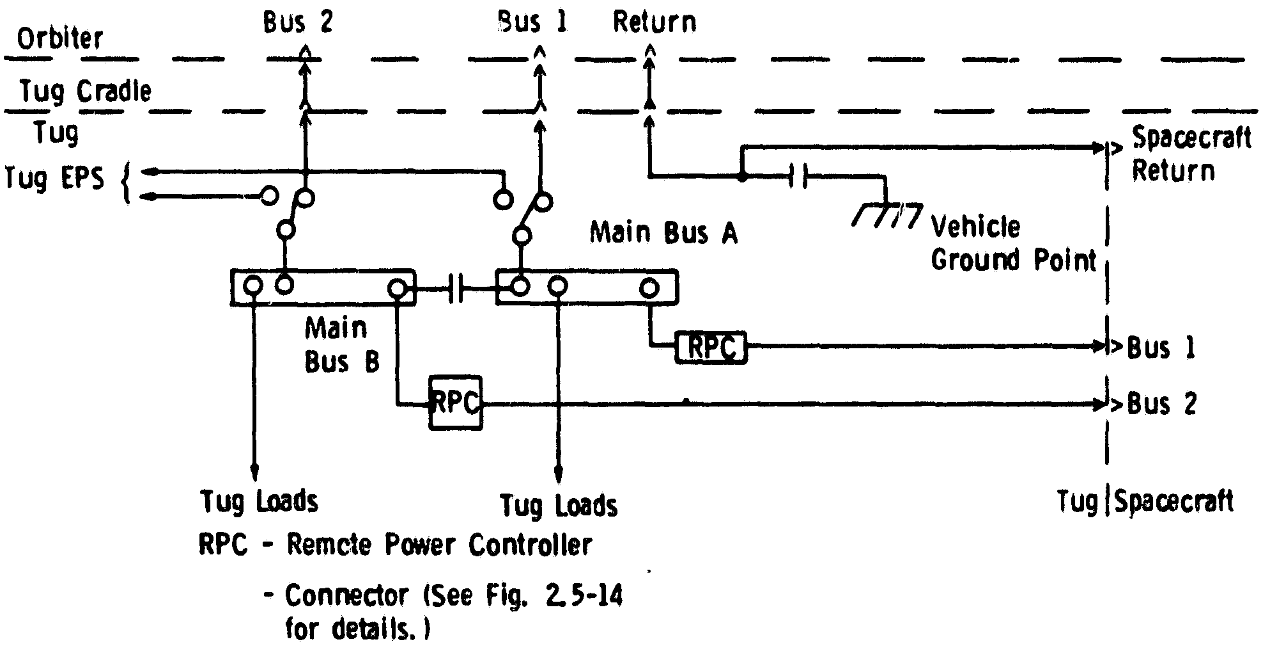


Fig. 2.5-13 Tug/Cradle/Orbiter and Tug/Spacecraft Electrical Interface

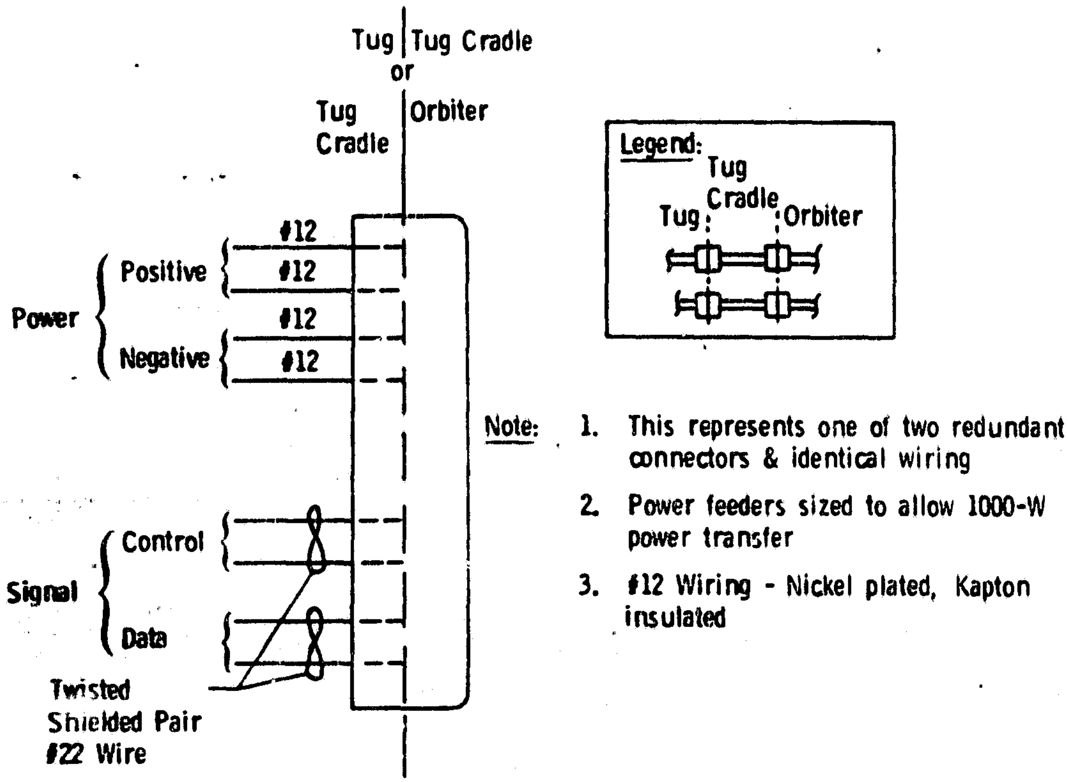


Fig. 2.5-14 Typical Tug/Tug Cradle/Orbiter Interface Connector/ Wiring

Software needed to program the Orbiter computer for Tug interface functions would vary from one mission to the next. The maximum software requirement would be for crew display functions.

c. Instrumentation - Tug has no separate instrumentation subsystem. The instrumentation function is included in the data management subsystem.

d. Guidance and Navigation - The Tug does not affect the Orbiter; i.e., there is no interface.

e. Communications - The Tug does not affect the Orbiter beyond the provisions of *Payload Accommodations* (Ref 5.13).

f. Caution and Warning - It is recommended that the Orbiter be provided with a caution and warning light on the standard Orbiter crewman's control consoles. This light would be activated by the Tug data management processor in response to out-of-limit Tug or spacecraft conditions. Software used with the one (of five) standard Orbiter computers assigned to the Tug on transport flights will allow the crewman to ask for and get more detailed data on Tug or spacecraft parameters through standard computer-interface keyboard addressing and cathode-ray-tube (CRT) display. Similarly, the crewman can exert override control of Tug functions.

2.5.4.2.2 Tug-Provided Equipment and Interface Status

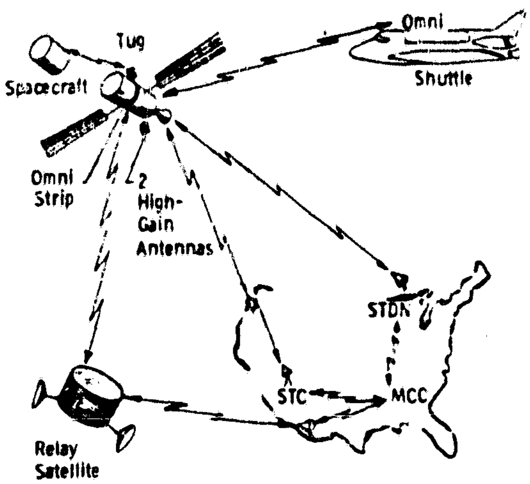
a. Electrical - Figure 2.5-13 illustrates the Tug side of the Tug/Orbiter electrical interface. Two remotely controlled switches control the power source from the Tug or Orbiter to the main buses of the Tug (two for redundancy). Two redundant Tug connectors, which mate with the Orbiter connectors, will be provided (Fig. 2.5-14) to transfer Orbiter power and return to the Tug and transmit all hard-wire control and data between the Tug and Orbiter. While mated electrically to Orbiter power, the Tug can use Orbiter ground return (structure ground) with ability to switch to the Tug ground point (a single-point ground) through the relay contact. Tug electrical energy requirements from the Orbiter are:

Time Power Required - T-0 to T-24 hr and Tug retrieval-to-Orbiter touchdown and secure	Energy Required - 16 kWh
	Average Power Required - 667 W
	Peak Power Required - 1000 W

b. Data Management - The interface box, identified in paragraph 2.5.4.2.1.b, will be provided to interface the Tug data management and Orbiter data processing subsystems.

c. *Instrumentation* - This function is included in the Tug data management subsystem.

d. *Communications* - Figure 2.5-15 shows the status of the communications interface. The Tug system is all S-band with gimbaled high-gain antennas, stripline omnidirectional antenna, FM and PM transmitters, receivers, power amplifiers, a coupling and switching network and coaxial cable harness. The system is redundant and is compatible with *Payload Accommodations* (Ref. 5.13).



Tug to Orbiter (or to Relay Satellite)

Mode Tug Configuration	Range, km*
2 W + Omni + 16 kbps	55 (31)
10 W + Omni + 16 kbps	12[illegible] (66)
2 W + Hi-Gain + 16 kbps	165[illegible] (990)
10 W + Hi-Gain + 16 kbps	4[illegible] (2220)
2 W + Omni + 2 kbps	16[illegible] (95)
10 W + Omni + 2 kbps	37[illegible] (200)
10 W + Hi-Gain + 2 kbps	11,600 (6,270)

*For detailed link calculations, see Vol 5.0, Sect. I, Para 2.3.3.2 c of Ref 5.8.

Fig. 2.5-15 Tug Communications

e. *Guidance and Navigation*

1) Guidance - There is Orbiter interface.

2) Navigation - There is no Orbiter interface; the Tug self-navigates from prelaunch on.

f. *Caution and Warning* - There is no dedicated hardware for caution and warning except the sensors (switches, transducers, etc) that allow the selected parameters to be monitored. The monitor, control, and data transmission to the Orbiter are via the data transmission subsystem for all parameters, through the control and data signal wires shown in Fig. 2.5-14. Due to the flexible-signal-interface approach, all parameters instrumented (for any reason) in the Tug could be transmitted as caution and warning parameters, eliminating the need to predetermine the desired parameters to monitor at this time (the only effect on the interface being in the software).

2.5.4.3 <u>Tug/Orbiter Fluid Interfaces</u>

2.5.4.3.1 <u>Tug Effects on Orbiter</u> - One nominal 3½-in. (8.89-cm) dia oxidizer and fuel dump line is required, which incorporates one half of a connector of the same diameter on the Tug/Orbiter interface end and incorporates a connector for GSE dumping on the other end. Provision will be required for in-flight dumping through these lines, which tentatively interface as shown in Fig. 2.5-16. The precise location of the interface will be determined in later work. The desired flow rate and allowable pressure drop in the Orbiter lines are shown in Fig. 2.5-17 for ascent abort.

2.5.4.3.2 <u>Tug-Provided Equipment and Interface Status</u> - Fuel and oxidizer dump lines will be required on the Tug cradle from the Tug/cradle interface to the cradle/Orbiter interface. These lines will be nominal 3½-in. (8.89-cm) dia and each (one fuel and one oxidizer) will incorporate one half of a reconnectable quick-disconnect coupling at the Tug/cradle interface in addition to a manual connector half at the cradle/Orbiter interface.

2.5.4.3.3 <u>Dump Philosophy and Characteristics</u>

a. Prelaunch - After main-tank propellants are loaded, trailers (GSE) will be provided for dumping, which may be either simultaneous or sequential and may be performed any time before terminal countdown. Either horizontal or vertical dumping capability is provided.

b. Ascent Abort - Dumping during powered flight should be limited to above 150,000 ft (47,720 m) to keep any propellant interaction to a very low order and allow simultaneous dumping in order to land empty. To meet a landing weight goal of 32,000 lb (14,515 kg) maximum, only oxidizer will be dumped. Figure 2.5-17 indicates the dump times.

c. On Orbit - Sequential or simultaneous dumping capability is provided and no Orbiter thrust is required during dumping; however, initial settling of Tug propellants by the Orbiter is required.

d. OME Kit/Tug Integrated Dump - Integrated dumping capability should be considered if the same propellants, dump rates, and similar tank pressures prevail for both the Tug and OME.

2.5.4.5 <u>Tug/Orbiter Operational Interface</u>

2.5.4.5.1 <u>Prelaunch Operations</u> - Prelaunch operations involve interface verification and a launch readiness (Fig. 2.5-18 shows Tug turn-around flow):

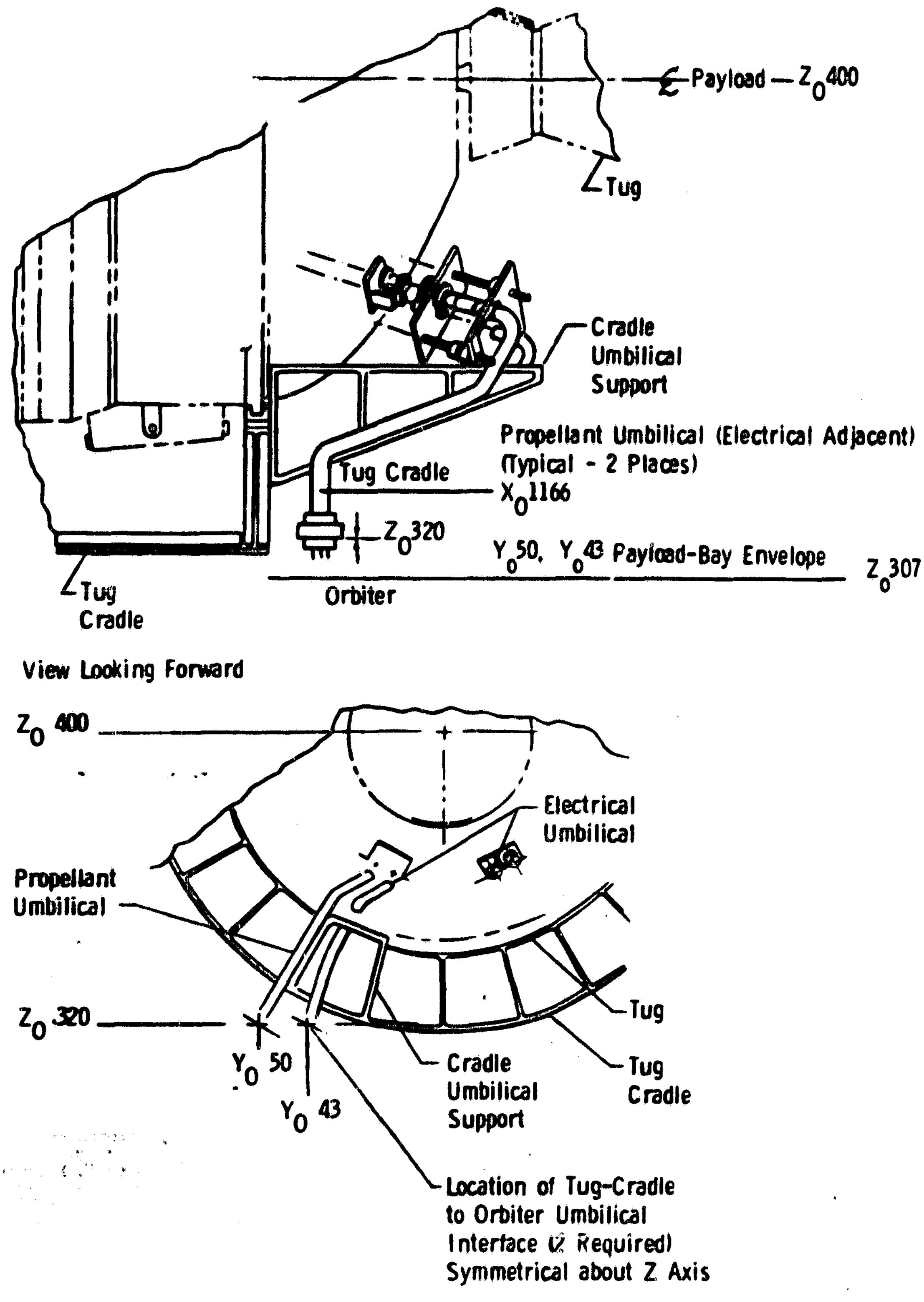


Fig. 2.5-16 Tug Cradle/Orbiter Fluid (Dump) Interface

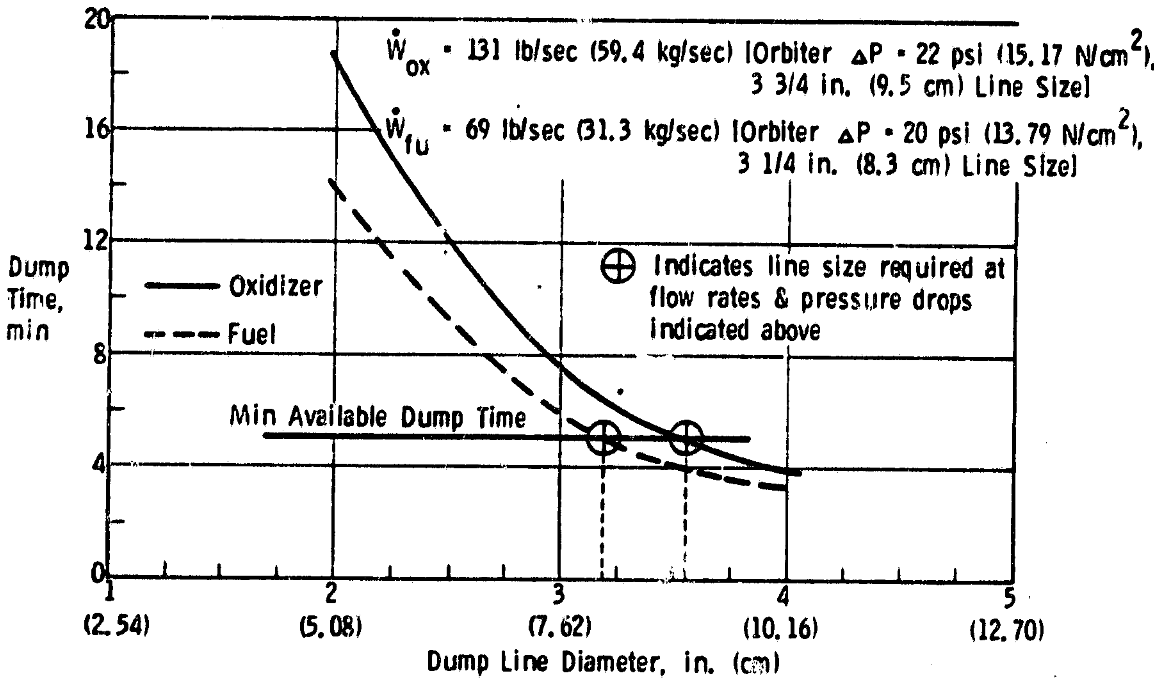


Fig. 2.5-17 Ascent Abort Dump Time vs Line Diameter

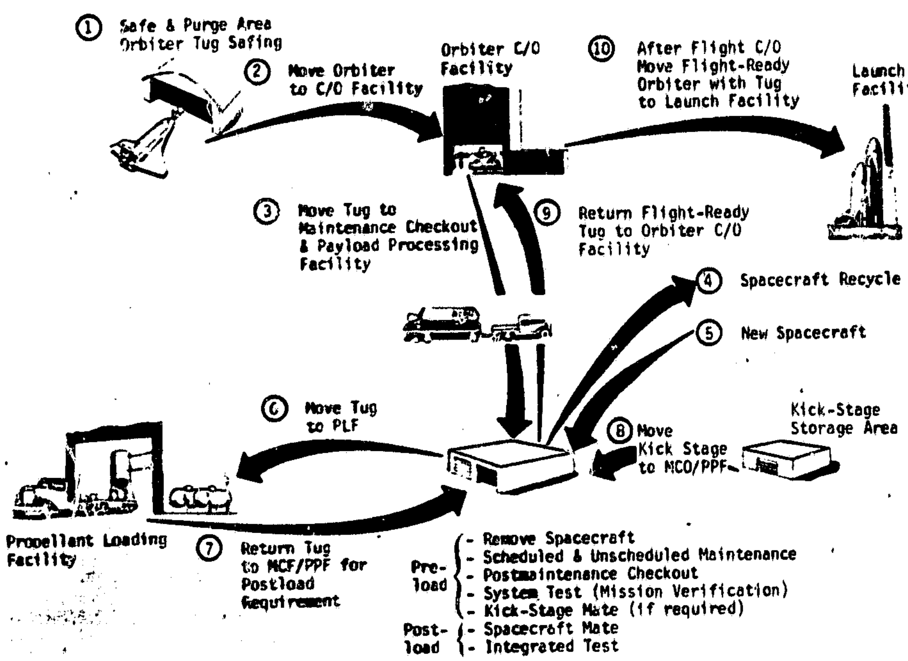


Fig. 2.5-18 Tug Turn-Around Flow Diagram

a. Interface Verification - Verification involves:

- Tug/cradle/Orbiter bay/RMS mate and verify compatibility;
- Tug/Orbiter umbilical mate (electrical and propellant) and verify compatibility;
- Tug avionics checkout using LPS and Tug/Orbiter on-board systems;
- Tug propellant dump trailers connected to Orbiter;
- Tug propellant temperature/pressure verified and monitored by LPS and Tug/Orbiter on-board systems;
- Orbiter-bay temperature/atmosphere monitored by LPS or other Orbiter GSE.

b. Launch Readiness - A countdown/countup via the LPS and Tug/Orbiter on-board systems is required.

2.5.4.5.2 <u>Flight Operations</u> - Flight operations involve launch and boost, on-orbit delivery and on-orbit retrieval.

a. Launch and Boost - The interface consists of status monitoring the Tug by the Orbiter-Tug data management system to the Orbiter data processing subsystem.

b. On-Orbit Deployment - The interface includes RMS deployment of Tug, power transfer from Orbiter to Tug, initiate RF control to Tug by Orbiter (Tug ACPS inactive), Orbiter status monitor of Tug, disconnect Tug umbilicals, RMS release of Tug, Orbiter/Tug separation, Tug ACPS activated in "large-limit-cycle" mode, and Orbiter "hand-over" control to Tug.

c. On-Orbit Retrieval - The interface includes Orbiter interrogate Tug status via RF, Tug ACPS acting in "small-limit-cycle" mode, RMS capture of Tug (ACPS deactivated), umbilical remate, power transfer to Orbiter, Tug system status monitor by Orbiter, Tug stowed in Orbiter bay.

2.5.4.6 <u>Tug/Orbiter Environmental Interfaces</u> - *Payload Accommodations* (Ref 5.13) specifies the environmental interface parameters of vibration levels, acoustic levels, shock levels, payload-bay atmosphere, and payload-bay wall. The Tug is compatible with these. It is requested that the Orbiter bay be maintained at 65 ± 5°F (18.3 ± 1.41°C) after Tug stowage until Shuttle liftoff, for Tug propulsion-system performance purposes.

2.5.4.7 Tug/Spacecraft Structural Interface

2.5.4.7.1 Tug Effect on Spacecraft

a. Each delivery-only spacecraft must have a structural adapter to be bolted to the separation module described in paragraph 2.5.4.7.2.a. below.

b. Each replacement spacecraft or retrieved spacecraft must have a structural adapter for mating to the docking module described in paragraph 2.5.4.7.2.b. below. The adapter will be attached in a manner similar to the Apollo probe-and-drogue method, with the drogue being part of the spacecraft adapter.

2.5.4.7.2 Tug-Provided Equipment and Interface Status

a. The separation module (Fig. 2.2-18 and 2.2-19) is used on all 10-ft (3.05-m) dia Tugs, with or without kick stages, which includes Final Options 1, 2, and 3. Final Option 3A is the same except the diameter is 6 ft (1.83 m). The baseline module consists of two machined angles spliced with two notched frangible doublers, with an oval stainless-steel tube in the splice. The angle flanges in each end of the 5-in. (12.7-cm) section bolt to the Tug or kick stage and spacecraft. Separation is achieved by detonating fuses inside the stainless tube, causing the frangible doublers to shear. After the doublers shear, final separation is achieved by springs around the inside perimeter of the module.

b. The docking module (Fig. 2.2-20) is used on all 10-ft (3.05-m) dia Tugs that have docking capability; namely, Final Option 2. The module consists of a 10-ft (3.05-m) dia shell, 21 in. (53.3 cm) deep, which houses a modified Apollo-type probe, an actuator-damper system, and 18 mechanical latches. The probe is mounted in the center of a triangular frame, which in turn is supported by six actuator-damper devices supported at the inboard flange of the module aft ring. A torque motor, mounted in the probe housing, provides spin-up for the probe head. Initial spacecraft capture is with capture latches mounted in the probe head. After initial capture, the actuator-dampers are retracted, and hard docking is achieved through 18 mechanical latches on the perimeter of the 10-ft (3.05-m) dia module.

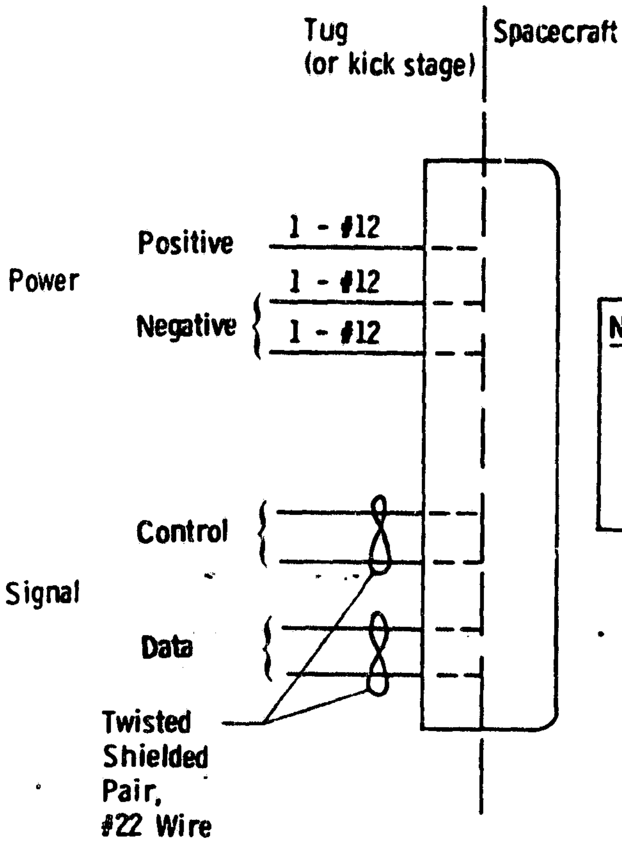
All flight loads are transmitted through the latches and outer structure, rather than through the docking mechanism. For a delivery and retrieval mission, the spacecraft is installed with hard latches and deployed by unlatching and extending the actuator-dampers. Option 3A uses the same method with a 6-ft (1.83-m) dia module.

c. Environmental parameters (vibration, shock, acceleration, and loads) imposed on the spacecraft will be a maximum of 120% of those imposed by the Orbiter.

2.5.4.8 Tug/Spacecraft Avionics Interface

2.5.4.8.1 Tug Effects on Spacecraft

a. *Electrical* - To receive power/signal data from the Tug, each spacecraft must provide two electrical interfacing connectors compatible with the interface shown in Fig. 2.5-19.



Note: 1. This represents one of two redundant connectors and identical wiring.
2. Power feeders sized to carry 450 W.
3. #12 Wiring - Nickel plated, Kapton insulated.

Fig. 2.5-19 Typical Tug/Spacecraft Interface Connector and Wires

b. *Data Management* - To provide Tug-to-spacecraft command, control, and checkout services, a spacecraft data management subsystem compatible with the Tug flexible signal interface is recommended for each spacecraft. This subsystem, patterned after and compatible with Tug (FORMAT and CLOCK), will interface through the two connectors (four signal pins per connector, two connectors for redundancy) and will provide for:

1) Either Tug, Orbiter, or GSE to issue any discrete commands, to gate and receive data from any telemetry channel, and transfer binary data to any compatible memory instrumented in the spacecraft;

2) Tug (when connected to the spacecraft) to provide limit check on any telemetry channel in the spacecraft and issue discrete commands in response to any spacecraft out-of-limit condition;

3) Tug limit check and general-purpose computer to be capable of automatically correcting out-of-limits or dangerous conditions in the spacecraft.

These provisions require a Tug-compatible CDTC processor and branch circuits in the spacecraft.

2.5.4.8.2 Tug-Provided Equipment and Interface Status

a. Electrical

1) Two redundant connectors will be provided, with the wiring type and size shown on Fig. 2.5-19 to mate with the spacecraft connectors.

2) Steady-state voltage of 22 Vdc minimum at 300 W will be provided by the Tug at the interface.

3) Ripple voltage at the Tug/spacecraft interface will be 4 V peak to peak while the Orbiter is supplying power to the Tug.

b. Data Management - Two four-pin interfaces will be provided in the connector to interconnect the Tug and spacecraft time-division multiplexed control and data lines.

2.6 SUPPORTING RESEARCH AND TECHNOLOGY

A supporting research and technology (SRT) program of $20 million has been designed to minimize risk and maximize confidence in developing a space transportation system that meets the performance, cost, and schedule goals established during this study contract.

All technology requirements were carefully examined by the Tug study team with full support of the technology specialists from the Research and Development Department. Completion of SRT tasks before the start of DDT&E will minimize cost and provide for a low-risk hardware program.

A list of SRT Tasks, their costs, schedules, and applicability to each of the final options is in Table 2.6-1.

The DOD R&D project test and evaluation program is the same as the NASA SRT program.

2.6.1 Tug SRT Tasks

Descriptions, schedules, and supporting data for each SRT task are in Vol 5.0 of the *Selected Option Data Dump* (Ref 5.8). One additional task, Avionics Task A-19, *Moving Base Docking Simulation*, applicable to the retrieval capability required for the 1983 IOC for Final Options 2, 3 and 3A, is described in the next paragraph.

2.6.1.1 Moving-Base Docking Simulation - A series of moving-base simulations will be required to study the remote and autonomous control of docking. Autonomy Level II will be baselined, which (by definition) includes both blind and man-in-the-loop docking. A worst-case rotating vehicle will be assumed. Because a rotating vehicle can (in the absence of friction or presence of a disturbing torque) be coning; this motion will also be examined. The propellant-slosh (0-g) models developed in SRT Task A-3 *Propellant Slosh Effects in Low-g Environment* will be included in the dynamics of the Tug model used to drive the moving-base simulator. Induced precession of the target vehicle will be modeled by the use of a small gimbaled target platform on an air-cushion floor. The docking logic will be incorporated in the dynamic model, which drives the primary moving-base simulator. The algorithm will be an expansion and iteration of the steering laws developed in SRT Task A-2 *Docking Strategies Assessment*. The candidate sensor sets will be: 1) RF (short range) augmented by video, with both artificial intelligence (on-board processing) and man-in-the-loop; 2) SLR augmented, as above, by video and SLR on its own. An IMU is always assumed.

Table 2.6-1 Support Research and Technology Cost and Schedule

Task No.	Task Title	Final Option 1		2		3		3A		Est Cost, $K	Schedule, m
		78	--	83	--	79	83	79	83		
	<u>STRUCTURES</u>										
S-1	Composite Material Characterization	X		X		X		X		169	18
S-2	Composite Joint Study	X		X		X		X		82	12
S-3	Failure Analysis for Composite Structures	X		X		X		X		264	18
S-4	Finite Elements for Composite Structures	X		X		X		X		316	18
S-5	Composite Honeycomb Assurance	X		X		X		X		150	14
S-6	Honeycomb Core Optimization	X		X		X		X		66	9
S-7	Lightweight Shell Structures	X		X		X		X		392	22
S-8	Investigate Facture Toughness of Thin-Gage Titanium, 6Al-4V	X		X		X		X		240	18
S-9	Composite Helium Pressurization Vessel	X		X		X		X		73	9
S-10	Crack Detection Sensitivity for Thin-Gage Liners & Joints	X		X		X		X		105	18
S-11	Analytical Methods for Composite Pressure Vessels	X		X		X		X		211	18
S-12	Liner Bonding for Helium Pressurization Vessel	X		X		X		X		52	11
S-13	Liner Manufacturing for the He Pressurization Vessel	X		X		X		X		66	8
S-14	Composite Overwrapped Tank Assurance	X		X		X		X		158	11
S-15	Propellant Behavior in Elastic Tanks	X		X		X		X		85	16
S-16	Dock & Capture of Elastic Spin Satellites			X			X		X	127	16
	<u>THERMAL</u>										
T-1	Reusability of Multilayer Insulation	X		X		X		X		323	18
T-2	Reusability of Tug Coatings	X		X		X		X		333	18
	<u>AVONICS</u>										
	<u>Rendezvous & Docking</u>										
A-1	Remote Manned and Autonomous Docking			X			X		X	1,070	16
A-2	Docking Strategies Assessment			X			X		X	815	36
A-3	Propellant Slosh Effects in Low-g Environment	X		X		X		X		257	18
A-4	RF Target Signatures			X			X		X	220	15
A-5	SLR Receiver Application as a Star Tracker			X			X		X	194	12
A-19	Moving-Base Docking Simulation			X			X		X	3,400	36
	<u>Guidance & Navigation</u>										
A-6	Terminal Phase Rendezvous Navigation & Guidance			X			X		X	257	24
A-7	Strategy Assessment for High-Volume Tug Operations	X		X			X		X	475	24
A-8	Target Vehicle Signatures as Star Tracker Targets			X			X		X	96	12
A-9	Autonomous Navigation Technology for Space Tug	X		X			X		X	106	12
A-10	Inertial Measurement Units Evaluation & Selection	X		X		X		X		1,055	13

Table 2.8-2 (concl)

Task No.	Task Title	Final Option 1 79	—	2 83	—	3 79	83	3A 79	83	Est Cost, $K	Schedule, m
	AVIONICS (concl)										
	Communications & Data Management										
A-11	Planar Array Antenna	X		X		X		X		99	12
A-12	One-Way Doppler & Emergency Command Receiver	X		X		X		X		242	15
A-13	Flexible Signal Interface	X		X		X		X		466	18
	Electrical Power										
A-14	Design of Roll-Up Solar-Array System	•		X		X		X		395	16
A-15	"Blue" Solar-Cell Evaluation			X		X		X		42	6
A-16	Battery Development & Evaluation	X		X		X		X		170	18
A-17	Multiplexed Power Dist Control & Monitoring System Development	X		X		X		X		260	12
A-18	Electromechanical Umbilical Connection System	X		X		X		X		255	14
	FLIGHT OPERATIONS										
F-1	Operability Analysis	X		X		X		X		1,268	18
	PROPULSION										
	Main Propulsion System (MPS)										
P-1	Long-Life Turbo Pump Assembly	X		X		X		X		1,000	15
P-2	Demo of Eng Restart Capability with Mission Duty Cycle	X		X		X		X		1,500	18
P-3	High-Area-Ratio Nozzle Performance			X			X		X	1,000	12
P-4	Engine Life, Maintenance & Refurbishment	X		X		X		X		200	8
P-5	Evaluation of Inspection, Cleaning, Maintenance for Propellant Management Device	X		X		X		X		49	12
P-6	Propellant Management Device Evaluation	X		X		X		X		21	4
P-7	Evaluation of Propellant Utilization System	X		X		X		X		49	8
P-8	Propellant Dump Technology	X		X		X		X		128	12
P-9	Propellant Compatibility & Corrosion	X		X		X		X		180	16
P-10	Effects of Engine Exhaust on Spacecraft	X		X		X		X		237	16
P-11	Fab Technology for Tug Propellant Mgmt Devices	X		X		X		X		271	10
	Attitude-Control Propulsion System (ACPS)										
P-12	Hydrazine Thruster Life & Reuse Demo Program	X		X		X		X		400	12
P-13	N_2H_4 Propellant Compatibility & Corrosion	X		X		X		X		132	15
P-14	Evaluation of Inspection, Cleaning, Maint for Propellant Management Device	X		X		X		X		50	8
P-15	Propellant Management Device Evaluation	X		X		X		X		17	4
	MANUFACTURING										
M-1	Improved Weld Technology, Domes & Barrels	X		X		X		X		74	18
M-2	Composite Structure Development	X		X		X		X		86	18
M-3	One-Piece Dome Fabrication, 2219 Al & 6-4 Ti							X		159	18
M-4	Screen Surface-Tension Device, Tank	X		X		X		X		54	18
	Total Final Option 1 - 1979 IOC									12,186	
	Total Final Option 2 - 1983 IOC									19,802	
	Total Final Option 3 - 1979 IOC									12,042	
	- 1983 IOC									7,760	
	Total Final Option 3A - 1979 IOC									12,201	
	- 1983 IOC									7,760	

Nominal and perturbed docking runs will be made. The pertubations are intended to cover those deviations in initial conditions and sensor and communication performance that are within specification. This effort will not include a single-point failure analysis.

The required schedule for Task A-19 is 36 months, and the estimated cost is $3,400,000. The cost is based on 750 man months of labor, $200,000 for computer, $175,000 for material, and $70,000 for hardware.

3.0 ADDITIONAL ANALYSIS

Additional analysis work that has been accomplished between the September *Selected Option Data Dump* (Ref 5.8) and submittal of this final report is summarized in the following paragraphs.

3.1 FINAL OPTION 3 ENGINE SENSITIVITY STUDY

3.1.1 Introduction

The Final Option 3 baseline is a phase-developed program that includes phasing of the engine from an OME 240 in the Phased Tug-Final. The rationale for phasing the engine was to minimize peak funding requirements early in the program.

The *Selected Option Data Dump* (Ref 5.8) included an engine sensitivity study that considered the impact of not phasing the engine. Three engines were considered. The results presented at that time are summarized in Table 3.1-1; additional details are presented in Vol 5.0, Sect. II, pages 6-1 through 6-8 of Ref 5.8.

Not phasing the engine results in savings in DDT&E costs and a reduction in yearly peak funding requirements. However, we were unable to select an engine at that time because total programmatics, including capture analysis and its effect on Tug and Shuttle costs had not been considered in the sensitivity study. (Note that the OME 240 and 8096B-2 show greater savings in engine costs than the Class I, but have less performance capability.)

The following paragraphs summarize the results of an engine sensitivity study for Final Option 3, based on total programmatics. Updated engine and vehicle performance data are also incorporated. Additional details are presented in Martin Marietta letter 73Y-81,182, dated October 19, 1973, Contract NAS8-29675, Option 3 Engine Sensitivity Study.

3.1.2 Summary of Results

Results are summarized in Table 3.1-2. Using a Class I engine in both the Phased Tug-Initial and Phased Tug-Final not only reduces the DDT&E costs by $36.2 million, but also reduces the number of flights required, resulting in lower transportation costs.

Use of the OME 240 or 8096B-2 engines in both the Phased Tug-Initial and Phased Tug-Final, results in lower DDT&E costs than the Class I (phased or not phased), but the number of flights is increased due to the lower performance, resulting in higher transportation and total program costs.

3.1.3 Recommendation

It is recommended that the Class I engine be used in both the Phased Tug-Initial and Phased Tug-Final for Final Option 3.

Table 3.1-1 Engine Sensitivity to Not Phasing Engines

Parameter of Interest \ Configuration	Final Option 3 Baseline*	Final Option 3 with OME 240 Engine	Final Option 3 with Class I Engine	Final Option 3 with 8096B-2 Engine
Performance Capability				
Delivery 1979, lb (kg)	4400 (1996)	4400 (1996)	5710 (2590)	5990 (2717)
Delivery 1983, lb (kg)	6000 (2722)	4690 (2127)	6000 (2722)	5410 (2454)
Retrieval 1983, lb (kg)	1800 (816.5)	1280 (580.6)	1800 (816.5)	1550 (703)
Cost Delta, $M				
DDT&E		-61.29	-36.17	-56.09
Investment		- 1.59	- 1.59	- 2.79
Operations		-12.10	- 4.22	-19.51
Total		-74.98	-41.98	-78.39
Schedule Effect OME 240 - No effect Class I - First flight vehicles have PFC performance 8096B-2 - No effect				
Technology Requirements No significant difference between engine options				
*OME 240 phased to Class I.				

Table 3.1-2 Summary of Results of Engine Sensitivity Study

	Baseline*	OME 240	Class I	8096B-2
Geostationary Performance Capability				
Delivery 1979, lb (kg)	4400 (1996)	4400 (1996)	5700 (2585)	4900 (2223)
Delivery 1983, lb (kg)	6000 (2722)	4500 (2041)	6000 (2722)	5100 (2313)
Retrieval 1983, lb (kg)	1800 (816.5)	1200 (544.3)	1800 (816.5)	1450 (657.7)
Number of Flights	352	391	344	375
Tug Fleet Size	16	18	16	18
Delta Engine Costs, $M				
DDT&E		-60.3	-36.2	-60.3
Prpduction		- 0.1	- 0.8	- 3.5
Operations		- 0.3	0.0	- 5.7
Total Delta		-60.7	-37.0	-69.5
Delta Tug Costs, $M		+48.1	-7.3	+33.6
Delta Shuttle Costs, $M		+409.5	-94.5	+241.5
Delta Program Costs, $M		+386.9	-138.8	+205.6

***Baseline: OME 240 phased to Class I.**

3.2 FINAL OPTION 3 SPECIAL SENSITIVITY STUDY (3SS-1) - IOC 1980

3.2.1 Introduction

The Initial Operational Capability (IOC) for the Final Option 3 baseline is December 1979 (ETR). An IOC sensitivity study option was presented in the *Selected Option Data Dump* (Ref 5.8), which showed the impact on funding requirements if the IOC date were slipped two years (Fig. 3.2-1). This showed that yearly funding requirements could be reduced; however, IOC dates for WTR and the Phased Tug-Final were delayed. This delay is undesirable for mission accomplishment and programmatics. A "valley" in the funding requirement occurs between peaks, similar to Final Option 3. It appears that the valley would be eliminated if all except the initial Final Option 3 IOC dates were retained. In addition, the sensitivity study indicated that there was no advantage in slipping the ETR IOC date more than one year.

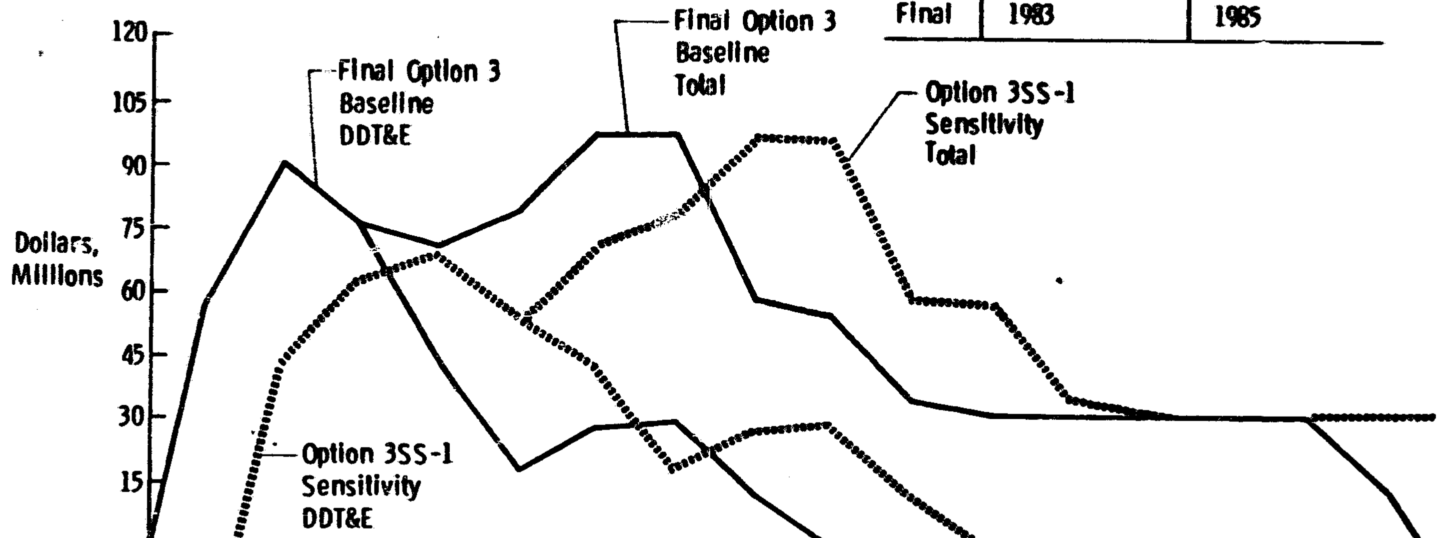
The purpose of this special sensitivity study, referred to as Option 3SS-1, is to determine the impact of delaying the IOC at ETR one year, while maintaining the Final Option 3 IOC dates for WTR and the Phased Tug-Final. There are no Shuttle restrictions on the number of flights in the first two years of operations; however, a reasonable build-up in Tug flights is included. Study details are presented in Martin Marietta letter 73Y-81,232, dated November 9, 1973, Contract NAS8-29675, Additional Cost and Schedule Data.

3.2.2 Summary of Results

Figure 3.2-2 presents the funding requirements for Option 3SS-1. The IOC for ETR has been delayed one year relative to Final Option 3, while the IOC for WTR and the Phased Tug-Final remain the same. A launch-rate build-up in the first two years of operations has been included. Funding requirements for DDT&E peak at $66.5M in FY 1979; the total funding requirements peak at $95M in FY 1981-1982. Note that there is no "valley" between the two peaks. This option provides a reasonable build-up in peak funding requirements.

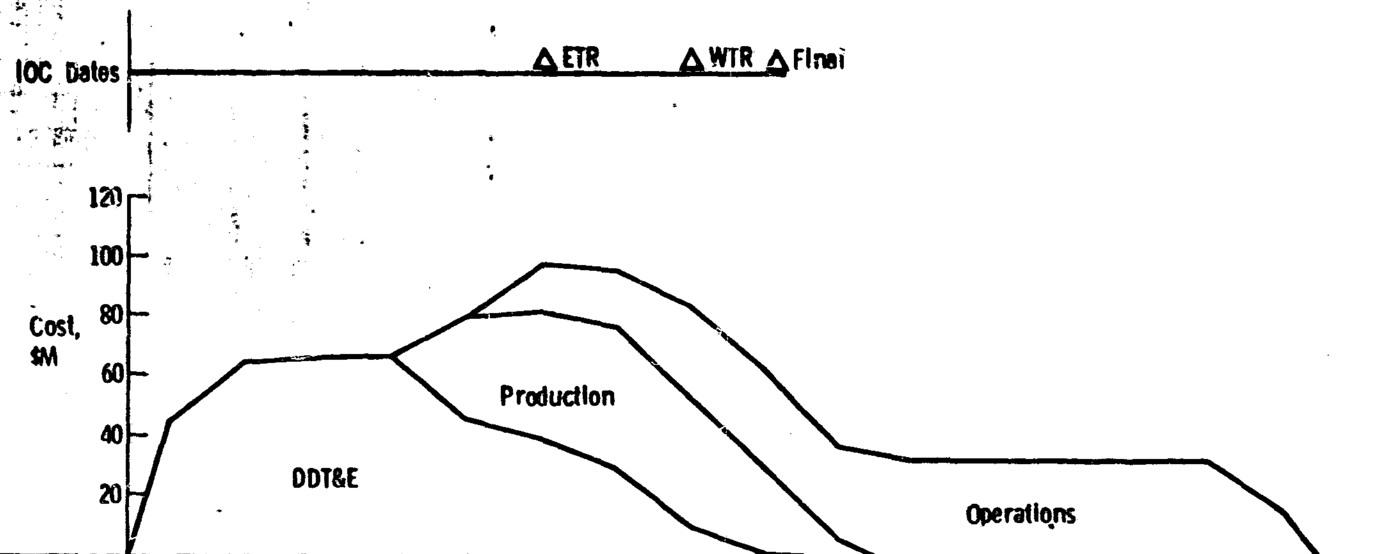
Figure 3.2-3 compares the total funding requirements for Option 3SS-1 with the Final Option 3 baseline and the IOC sensitivity-study option presented in the *Selected Option Data Dump* (Ref 5.8). Delaying the Option 3SS-1 ETR IOC one year reduces the peak DDT&E funding requirement (relative to the Final Option 3 baseline) by $24M, which is approximately the same as that for the IOC sensitivity study option. The level in total peak funding requirements remains the same as the Final Option 3 baseline and the IOC sensitivity study option; however, the peak occurs at the same time as the Final Option 3 baseline (two years earlier than the IOC sensitivity study option).

IOC Dates (Dec)	Final Option 3 Baseline	Option 3SS-1 Sensitivity
ETR	1979	1981
WTR	1982	1984
Final	1983	1985



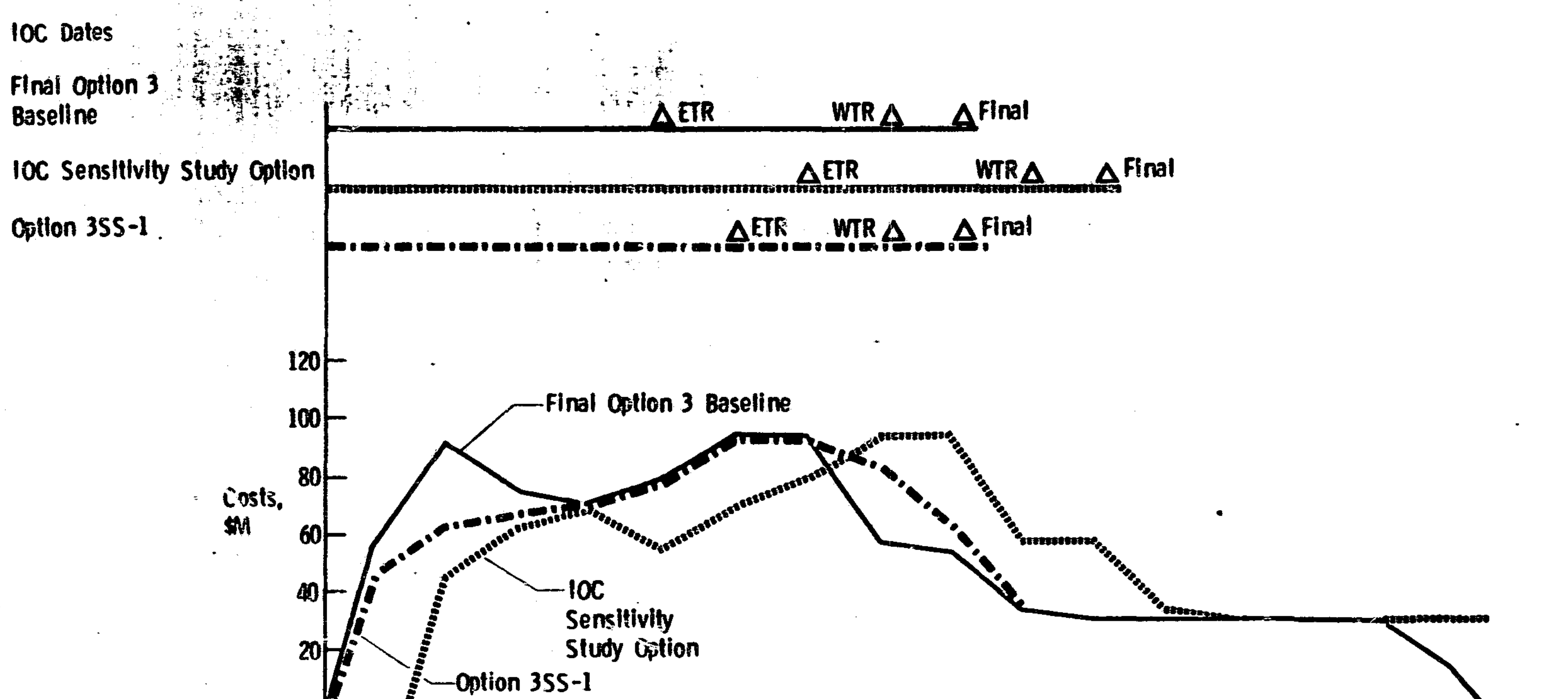
FY	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91
DDT&E																
Final Option 3 Baseline	54.7	90.8	76.1	44.3	18.1	27.9	29.5	11.8	0.6							
Option 3SS-1 Sensitivity		44.0	62.0	68.0	55.0	44.3	18.1	27.9	29.5	11.8	0.6					
Total																
Final Option 3 Baseline	54.7	90.8	76.1	70.3	79.7	95.7	95.2	58.8	55.1	34.8	31.1	31.3	31.2	31.1	31.3	14.6
Option 3SS-1 Sensitivity		44.0	62.0	68.0	55.0	70.3	79.7	95.7	95.2	58.8	58.1	34.8	31.1	31.3	31.2	31.1

Fig. 3.2-1 Funding Requirements for Option 3SS-1 Sensitivity vs Final Option 3 Baseline



FY	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	Total
DDT&E	44.0	62.0	65.0	66.5	43.5	38.2	29.2	11.8	0.6								361.1
Production					36.0	42.6	47.2	42.7	30.0	5.6							204.1
Operations						14.8	18.8	28.9	30.[illegible]	31.1	31.1	31.3	31.0	31.1	31.3	14.5	294.8
Total	44.0	62.0	65.0	66.5	79.5	95.6	95.2	83.4	61.5	36.7	31.1	31.3	31.0	31.1	31.3	14.5	860.0

Fig. 3.2-2 Funding Requirements for Option 3SS-1 for ETR IOC December 1980



FY	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	Total
Final Option 3 Baseline	54.7	90.8	76.1	70.3	79.7	95.7	95.2	58.8	55.1	34.8	31.1	31.3	31.2	31.1	31.3	14.6	880.9
IOC Sensitivity Study Option		44.0	62.0	68.0	55.0	70.3	79.7	95.7	95.2	58.8	58.1	34.8	31.1	31.3	31.2	31.1	846.3
Option 3SS-1	44.0	62.0	65.0	66.5	79.5	95.6	95.2	83.4	61.5	36.7	31.1	31.3	31.0	31.1	31.1	14.5	860.0

Fig. 3.2-3 Comparison of Total Funding Requirements

Option 3SS-1 provides the advantages of low DDT&E peak funding early in the program (similar to the IOC sensitivity study option), earlier operational capability at WTR and for the Phased Tug-Final than the IOC sensitivity study option, and eliminates the valley between funding peaks.

Table 3.2-1 compares total costs for Option 3SS-1 with the Final Option 3 baseline. DDT&E costs for Option 3SS-1 are slightly higher because the span time for level-of-effort tasks to develop the Phased Tug-Initial is increased by one year. This is somewhat offset by using only one shift to build the first Tug and major test articles. Production costs are reduced because fewer kick stages and separation modules are required. Operations costs are reduced because the operational span time is one year shorter and a build-up of crew size is used. The number of flights is reduced by 13 due to the elimination of three flights in 1980 and the build-up in 1981 and 1982.

Table 3.2-1 Cost Comparison

	Final Option 3 Baseline, $M	Final Option 3SS-1, $M
Tug Costs		
DDT&E	354	361
Production	209	204
Operations	318	295
Total Tug	881	860
Number of Flights	352	339
Operations Cost/Flight	0.90	0.87
Shuttle Costs	3696	3560
Transportation Cost	4577	4420

3.2.3 Recommendation

Option 3SS-1 is recommended over the Final Option 3 baseline and the IOC sensitivity study option for the following reasons:

1) Early DDT&E peak funding is reduced relative to Final Option 3.

2) The operational capability for WTR and the Phased Tug-Final is retained (two years earlier than the IOC sensitivity study option).

3) The valley between peak funding requirements is eliminated, providing a reasonable build-up in peak funding requirements.

4) A reasonable build-up in flight rate and crew size is provided at both ETR and WTR.

3.3 FINAL OPTION 3 SPECIAL SENSITIVITY STUDY (3SS-2) - IOC 1980, ENGINE NOT PHASED

3.3.1 Introduction

A special sensitivity study (Option 3SS-1, para 3.2) indicated that a phased development program with an initial IOC date of December 1980 and final IOC date of December 1983, provided a more reasonable funding distribution than either the Final Option 3 baseline or its IOC sensitivity study option presented in the *Selected Option Data Dump* (Ref 5.8). Operational costs were also reduced by building up the launch rate and crew size at ETR in 1981 and 1982.

Engine sensitivity studies (para 3.1) indicated that the engine should not be phased and that the Class I engine should be used for both the Phased Tug-Initial and Phased Tug-Final (Table 3.1-2). This will reduce DDT&E costs.

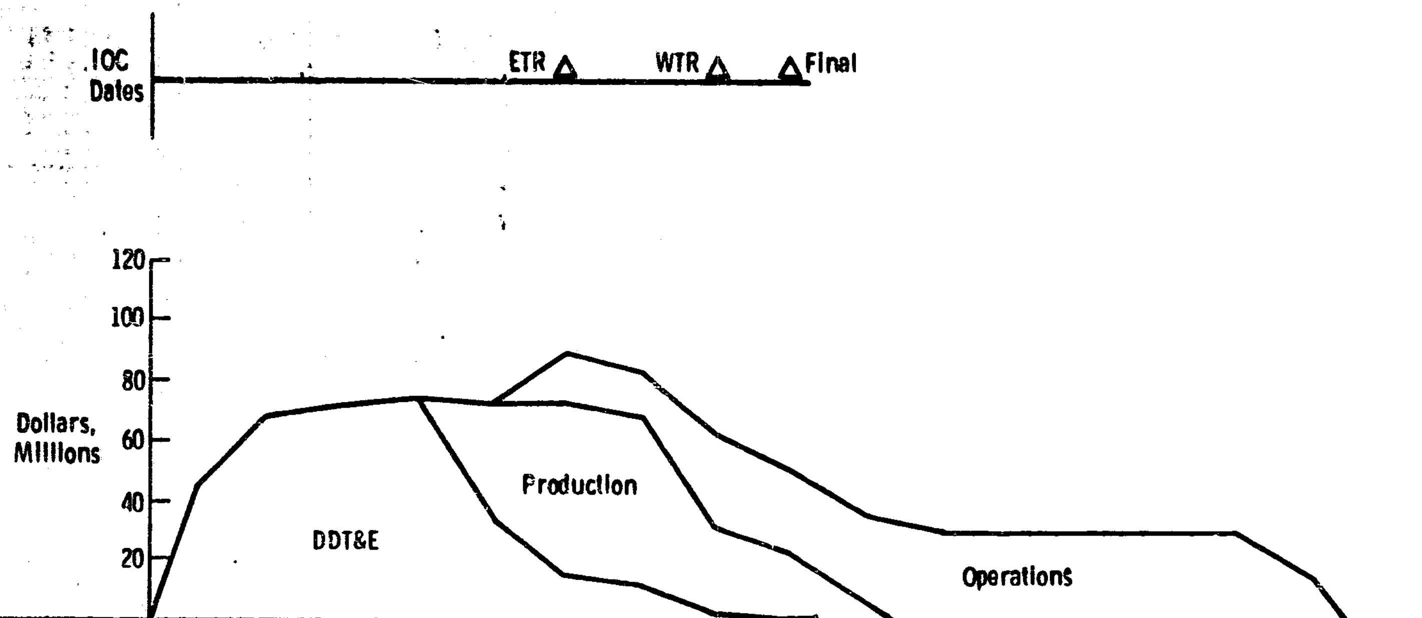
The purpose of this special sensitivity study was to combine the sensitivity studies previously discussed to provide programmatics for a phased development program with an initial IOC date of December 31, 1980, and a final IOC date of December 31, 1983, with the Class I engine not phased. This special sensitivity study is referred to as Option 3SS-2. Additional study details are presented in Martin Marietta letter 73Y-81, 239, dated November 14, 1973, Contract NAS8-29675, Additional Cost and Schedule Data, Engine Not Phased.

3.3.2 Summary of Results

Figure 3.3-1 presents the funding requirements for Option 3SS-2. The IOC for ETR has been delayed one year relative to Final Option 3, while the IOC dates for WTR and the Phased Tug-Final remain the same. The Class I engine is not phased. Launch rate limitations in the first two years of operation are the same as in Option 3SS-1. Funding requirements for DDT&E peak at $74.1 million in FY 1979; total funding requirements peak at $87.8 million in FY 1981. This option provides a reasonable build-up in yearly funding requirements similar to Option 3SS-1.

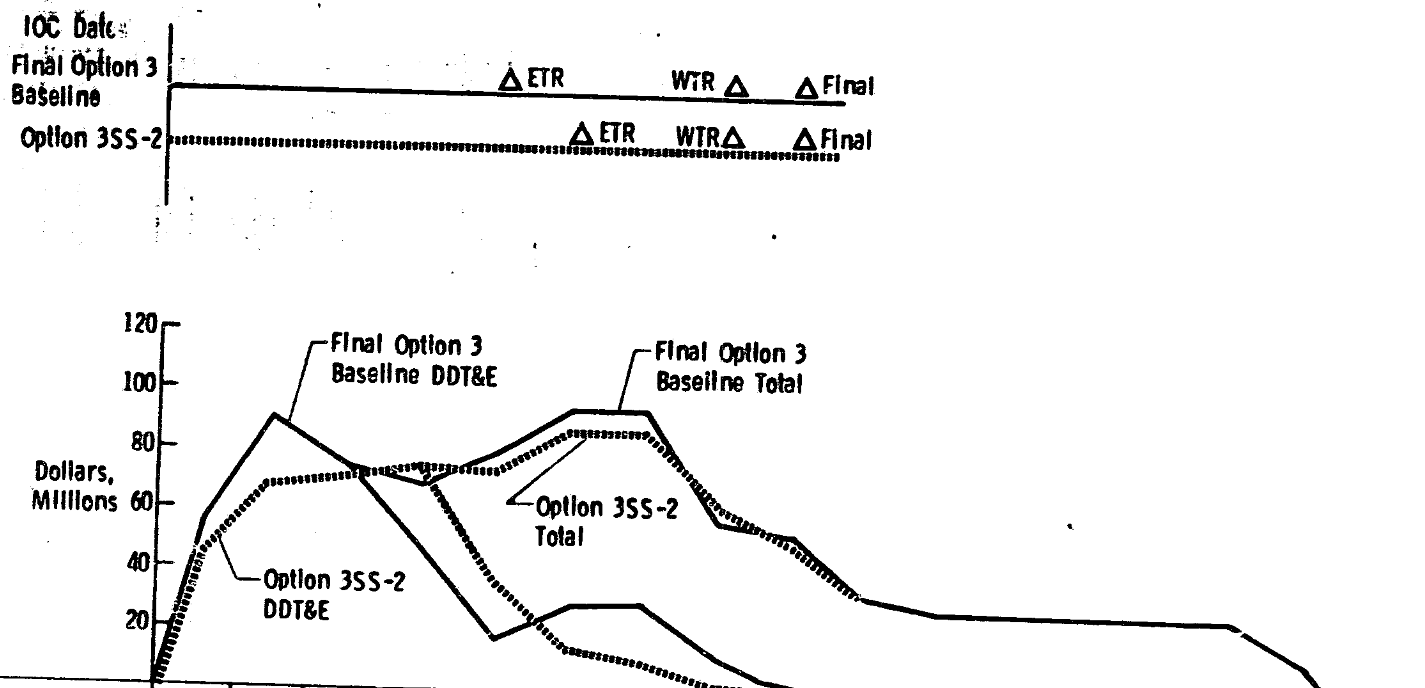
Figure 3.3-2 compares the DDT&E and total funding requirements for Option 3SS-2 with the Final Option 3 baseline. As was the case with Option 3SS-1, delaying the IOC date one year reduces DDT&E peak funding requirements. Because the second engine development is not required, DDT&E costs are reduced in the FY 1981-1982 time period, lowering the total peak funding requirements.

The valley between the peaks shown for the Final Option 3 baseline is eliminated in Option 3SS-2, providing a more reasonable funding distribution.



FY	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	Total
DDT&E	44.4	68.4	72.6	74.1	36.9	15.0	11.7	1.2	0.6								324.9
Production					35.9	58.0	56.1	31.2	20.9	5.6							207.7
Operations						14.8	18.8	28.8	30.8	31.1	31.1	31.3	31.0	31.1	31.3	14.5	294.6
Total	44.4	68.4	72.6	74.1	72.8	87.8	81.6	61.2	52.3	36.7	31.1	31.3	31.0	31.1	31.3	14.5	827.2

Fig. 3.3-1 Funding Requirements for Option 3SS-2 for ETR IOC December 1980, Engine Not Phased



FY	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	Total
DDT&E																	
Final Option 3 Baseline	54.7	90.8	76.1	44.3	18.1	27.9	29.5	11.8	0.6								353.7
Option 3SS-2	44.4	68.4	72.6	74.1	36.9	15.0	11.7	1.2	0.6								324.9
Total																	
Final Option 3 Baseline	54.7	90.8	76.1	70.3	79.7	95.7	95.2	58.8	55.1	34.8	31.1	31.3	31.2	31.1	31.3	14.6	881.3
Option 3SS-2	44.4	68.4	72.6	74.1	72.8	87.8	86.6	61.2	52.3	36.7	31.1	31.3	31.0	31.1	31.3	14.5	827.2

Fig. 3.3-2 Comparison of Funding Requirements

Table 3.3-1 compares total costs for Option 3SS-2 with the Final Option 3 baseline and Option 3SS-1. DDT&E costs are reduced by not phasing the engine (-$36 million); however, this is somewhat offset by increasing the DDT&E span time relative to the Final Option 3 baseline (+$7 million). Production costs are reduced slightly (relative to Final Option 3 baseline) due to learning-curve effects on the engines and reduction of separation modules. As was the case in Option 3SS-1, operations costs are reduced because the operational span time is reduced one year and a build-up of crew size is used.

Table 3.3-1 Cost Comparison

	Final Option 3 Baseline	Option 3SS-1	Option 3SS-2
Tug Costs, $M			
DDT&E	354	361	325
Production	209	204	208
Operations	318	295	295
Total Tug	881	860	828
Number of Flights	352	339	336
Operations Cost/Flight	0.90	0.87	0.88
Shuttle Costs	3696	3560	3528
Transportation Costs	4577	4420	4356

The number of flights is reduced due to the elimination of three flights in 1980, the build-up in 1981, and the increased performance capability of the Phased Tug-Initial with the Class I engine. Option 3SS-2 requires three fewer flights for 100% in 1983 and achieves 100% capture in 1982 with the build-up limitations imposed. (Option 3SS-1 does not achieve 100% capture in 1982.)

3.3.3 Recommendation

Option 3SS-2 is recommended over the Final Option 3 baseline and Option 3SS-1 for the following reasons:

1) Early DDT&E peak funding is reduced relative to the Final Option 3 baseline.

2) DDT&E costs are reduced by not phasing the engine.

3) The operational capability for WTR and Phased Tug-Final is retained.

4) The valley between peak funding requirements is eliminated, providing a reasonable build-up in peak funding requirements.

5) A reasonable build-up in flight rate and crew size is provided at both ETR and WTR; 100% capture is achieved in 1982.

6) The number of flights required to achieve 100% capture in 1983 is reduced.

3.4 CENTRALIZED TUG MAINTENANCE AND CHECKOUT FACILITY TRADE STUDY

3.4.1 Introduction

The purpose of this study was to investigate the feasibility of using a centralized tug maintenance and checkout facility (CTMCF), as opposed to separate maintenance and checkout operations at both KSC and WTR, the following items were considered:

1) Active fleet size;

2) Crew size and skill mix;

3) Facility and GSE requirements;

4) Logistics support, depot activities, and spares provisioning;

5) Tug turnaround time and active fleet size impacts;

6) Hazards or risks associated with additional handling and transportation;

7) Major Tug overhaul/refurbishment;

8) Launch site activities.

Additional details are presented in Martin Marietta letter 73Y-81, 129, dated October 8, 1973, Contract NAS8-29675, Space Tug Central Checkout Facility Trade Study.

3.4.2 Summary of Results

The CTMCF concept is a realistic and economical approach to Tug maintenance and checkout. Final Options 2, 3, and 3A realize a substantial savings in total program costs. In adapting to a central facility, Final Option 1 would cause an increase of less than $1M in total program cost. Table 3.4-1 summarizes the major cost deltas that would be realized if a CTMCF concept were adopted.

All costs are directly related to data presented in Vol 6.0, Sect. II, and Vol 8.0, Sect. II of Ref 5.8, and are listed in thousands of dollars.

Table 3.4-1 Delta Cost Summary

	Cost, $ Thousands			
	Final Option 1	Final Option 2	Final Option 3	Final Option 3A
Net Reduction - Active Tug Fleet	0	1	1	1
Savings - Production	0	8,504	8,375	8,131
Savings - Operations	-5,958	8,604	16,041	20,402
Savings - Facilities	5,160	5,160	5,160	5,160
Total Savings	- 798	22,268	29,576	33,693

The advantages of going to a centralized checkout facility outweigh those for separate facilities, both from a programmatics and an operational standpoint. Program cost will be lower as a result of reducing GSE, number of Tugs required in the active fleet, and, depending on launch rate, the number of personnel required. One of the biggest advantages not directly relatable to cost is the efficiency and consistency obtained by doing all maintenance, refurbishment, and basic Tug checkout at one facility. The problems that arise as a result of two separate facilities; i.e., configuration control, inventory, software and procedure update, crew training, etc are virtually eliminated.

The location selected for this centralized facility can affect Tug fleet size; therefore, it is recommended that the centralized facility be at the most active Tug launch site.

3.4.3 Recommendation

It is recommended that, for optimum use of Tug-related hardware, manpower, and program resources, a central maintenance and checkout facility concept be adopted and that it be located at KSC.

3.5 TUG PROPELLANT LOADING LOCATION TRADE STUDY

3.5.1 Introduction

The purpose of this trade study was to investigate the merits of loading a storable-propellant (hypergolic) Space Tug in various locations at the launch site. Four locations were considered for Tug propellant loading:

1) On Orbiter with cargo bay doors open;

2) On Orbiter with cargo bay doors closed;

3) On pad in payload changeout unit on access tower;

4) Off pad in propellant loading area.

The following items were considered for each of the four loading locations:

1) Safety;

2) Shuttle timelines;

3) Servicing interfaces;

4) Storage capability;

5) Spills during loading;

6) Reliability;

7) GSE;

8) Facilities;

9) Tug weight and cost;

10) Access;

11) Crew size;

12) Operational costs;

13) Cleanliness;

14) Security.

3.5.2 Summary of Results

While Tug propellant loading has some advantages at each of the four locations studied, propellant loading on the pad appeared to have several distinct advantages over loading at other locations. The preferred propellant loading location, in decreasing order of preference, is:

1) On pad in payload changeout unit on access tower;

2) On orbiter with cargo bay doors open;

3) Off pad in propellant loading area;

4) On Orbiter with cargo bay doors closed.

3.5.3 Conclusions

The advantages of Tug propellant loading on the launch pad outweigh propellant loading on the Orbiter and off the pad. Program costs can be reduced below costs involved in off-pad loading, and Tug access and safety are improved over loading on the Orbiter with the doors open.

By coupling this approach with the centralized tug maintenance and checkout facility (CTMCF), all of Tug-oriented facilities at WTR can be eliminated. After WTR receives the Tug from the CTMCF, it would be placed in the on-pad clean room for R&I and systems-level checks. The spacecraft would then be mated, systems checks performed, propellant loaded, and the payload mated to the Orbiter. This same approach could be used at KSC to reduce the number of test cells and the size of the Tug MCF.

3.6 COST SAVINGS

3.6.1 Introduction

The cost estimates for the final options were based on certain assumptions and ground rules, some of which we believe to be conservative. After the *Selected Option Data Dump* (Ref 5.8), the ground rules and assumptions were reviewed and potential cost savings identified relative to each final option.

3.6.2 Summary of Results

Table 3.6-1 presents a list of potential cost savings relative to each final option as presented in the *Selected Option Data Dump* (Ref 5.8), and a brief discussion of the rationale for each. The items are presented so that cost savings are additive.

3.6.3 Recommendation

It is recommended that the cost savings shown in Table 3.6-1 be incorporated. The resulting revised cost summary is presented in Table 3.6-2 to show the total effect of the cost savings. DDT&E costs for kick stages are not included.

Table 3.6-1 Summary of Cost Savings for All Final Options

Proposed Cost-Reduction Item	Discussion	Savings, $ Thousand				
		Cost Type	Final Option 1	Final Option 2	Final Option 3	Final Option 3A
1. Life Test Article	Fracture analysis & coupon test sufficient to verify tank structure.	DDT&E	3,737	3,947	3,888	4,039
2. Thermal Effects Test Model (TETM)						
a. Thermal Balance	Perform on first flight vehicle if unable to assure design by analysis. No previous programs for analysis verification.	DDT&E	5,189	5,560	5,531	9,271
b. Hot Firing	Sufficient test should be accomplished on Propulsion Test Vehicle (PTV) & at engine contractors without conducting all-up firing or TETM.	DDT&E	2,741	2,886	4,811	4,896
3. Kick Stage Thermal	Perform by analysis only.	DDT&E	605	562	605	605
4. Reduce Number of Cradles by 3 each (2 for Final Option 1)	Assume no losses due to damage of Orbiter. Minimum required is then 5 each.	Prod.	706	1,014	1,014	1,014
5. On-Pad (out of Orbiter) Propellant Loading instead of off-pad.	Eliminate requirement for Propellant Loading Facility (PLF) buildings; however, a modification cost would be realized to upgrade the launch complex. Assume 30% of current cost of PLF.	DDT&E	2,217	2,217	2,217	2,217
6. Central Tug Maintenance & Checkout Facility (CTMCF): use existing facility; delete cleanliness requirements.	CTMCF improves efficiency, reduces fleet size, crew & GSE. Use of existing facility without Class 100,000 cleanliness requirements reduces cost by 85%.	DDT&E	12,278	12,278	12,278	12,278
		Prod.	3,330	13,004	12,875	12,631
		Ops	-5,958	8,604	16,041	20,402
	Item 6 Subtotal		9,650	33,886	41,194	45,311
7. Do not phase engine. Initial IOC in Dec 1980 & final IOC in Dec 1983. Provide flight build-up in 1981 (Option 3BS-2)	Sensitivity studies indicate DDT&E costs & number of flights can be reduced by not phasing Class 1 engine. Delaying initial IOC 1 year reduces DDT&E peak funding; build-up reduces crew size.	DDT&E	—	--	28,800	28,800
		Prod.	—	--	1,600	10,100
		Ops	—	--	23,700	23,502
	Item 7 Subtotal				54,100	62,402
8. Delete procurement & maintenance of control center equipment.	Provided by the government using existing equipment and personnel. Not charged to Tug.	DDT&E	2,340	2,787	3,200	3,471
		Ops	3,302	2,337	3,121	3,[illegible]
	Item 8 Subtotal		5,642	5,124	6,321	6,592
9. Provide 5 Tug field reps in lieu of control center crew.	Control center crew provided by government. Not included in Tug costs.	Ops	11,597	8,866	11,597	11,597
10. Train NASA & DOD crews jointly.	Reduce duplication of effort.	Ops	580	523*	580	580
11. Extend DDT&E 1 Year (Option 2 only)	Increases total DDT&E cost but reduces program peak-year funding.	DDT&E	—	(7,400)	--	--
12. Acceptance Testing in CTMCF for Tug No. 3 thru 15	GSE requirements are reduced & there is no change in crew size.	DDT&E	—	2,300	2,700	2,700
		Prod.	3,200	2,300	3,200	3,200
	Item 12 Subtotal		3,200	4,600	5,900	5,900
13. Miscellaneous Corrections	Adjustments in cost baseline.	DDT&E	(1,200)	(100)	600	600
		Prod.	1,200	--	--	--
		Ops	8,300	5,700	7,500	7,000
	Item 13 Subtotal		8,300	5,600	8,100	7,600
	Total DDT&E Savings		27,907	25,037	64,630	68,877
	Total Production Savings		8,436	16,318	18,689	26,945
	Total Operations Savings		17,821	26,030	62,539	66,202
	Total Savings		54,164	67,385	145,858	162,024

Prod. = Production

Ops = Operations

Table 3.6-2 Revised Cost Summary

	Costs, \$M			
	Revised Option 1	Revised Option 2	Revised Option 3	Revised Option 3A
Tug Costs				
SRT	(12.2)	(19.8)	(19.8)	(20.0)
DDT&E	183	254	263	286
Production	158	153	190	361
Operations	224	208	256	261
Total	565	615	709	908
Number of Flights	227	254	336	331
Average Ops Cost per Flight	0.99	0.82	0.76	0.79
Shuttle Costs	2384	2667	3528	3476
Transportation Cost	2949	3282	4237	4384

( ) Not included in totals

3.7 Revised Option Definitions

3.7.1 Introduction

The sensitivity studies presented in the *Selected Option Data Dump* (Ref 5.8) and additional analysis presented in this report indicate that the final option definitions should be revised as follows:

- Delete life test article and thermal-effects test article;
- Assume no cradle attrition;
- Load propellants and install spacecraft on pad (but out of Orbiter);
- Use central tug maintenance and checkout facility (CTMCF), use existing facility, delete Class 100,000 cleanliness requirement;
- Assume control-center equipment and maintenance provided as GFP (existing equipment);
- Assume control-center crew provided by the government; do not include in Tug costs;
- Train NASA and DOD crews jointly;
- Do not include DDT&E costs for kick stages in Tug costs;
- For Option 2, start DDT&E one year earlier;
- For Options 3 and 3A, do not phase the engine, delay initial IOC one year, do not provide 100% capture in 1981;
- Perform acceptance testing in CTMCF.

Accordingly, this section presents the "revised option definition," which incorporate these revised ground rules and assumptions.

3.7.2 Summary of Results

Table 3.7-1 presents the requirements for the revised option definitions. Cost savings items are identified in paragraph 3.6.1. Because all Tug candidates (interim, cryogenic, or storable) require kick stages, which are not well defined, DDT&E costs for kick stages are not included in the total costs. DDT&E is started one year earlier in Revised Option 2 to reduce annual peak funding requirements. The engine is not phased in Revised Options 3 and 3A, and the IOC for the Phased Tug-Initial at ETR is delayed one year. A build-up in flight rate and crew size is also provided at WTR and ETR rather than drive the program directly to 100% capture in 1981.

Table 3.7-1 Revised Option Definitions and Requirements

	Revised Option 1	Revised Option 2	Revised Option 3	Revised Option 3A
IOC	1979	1983	1980/1983	1980/1983
Payload Requirement				
Delivery	3500 lb (1588 kg)	3500 lb (1588 kg)	3500 lb (1588 kg)	3500 lb (1588 kg)
Retrieval	--	3500 lb (1588 kg)	2200 lb (998 kg)	2200 lb (998 kg)
Vehicle	Single stage	Single stage	Single stage	Stage-and-a-half
Additional Requirements	Delivery-only Low DDT&E dollars No Growth 36-hr max duration	Direct-developed Delivery & retrieval in 1983	Phase-developed Delivery-only 1980 - 1983 Retrieval & increased performance in 1983	Phase-developed Delivery-only 1980 - 1983 Retrieval & increased performance in 1983
Revisions to Final Option Definitions	Cost savings items incorporated No DDT&E costs for kick stages	Cost savings items incorporated No DDT&E costs for kick stages Start DDT&E one year earlier	Cost savings items incorporated No DDT&E costs for kick stages Engine not phased ETR IOC delayed one year Flights restricted in 1981	Cost savings items incorporated No DDT&E costs for kick stages Engine not phased ETR IOC delayed one year Flights restricted in 1981

Table 3.7-2 presents a summary of the revised option definitions, including physical characteristics, performance capability, and identification of major subsystems. Dry weights and performance capabilities for the initial delivery Tugs in Options 3 and 3A have been revised as a result of using the Class I engine.

Table 3.7-3 presents the significant programmatic factors for the revised option definitions. The operational span time for Revised Options 3 and 3A has been reduced from 11 to 10 years by delaying the initial IOC. Crew sizes have been reduced, except for Option 1, by use of a centralized tug maintenance and checkout facility (CTMCF). The number of flights for Revised Options 3 and 3A have been reduced as a result of not phasing the engine, the shorter operational span time, and not driving the program to 100% capture in 1981. Fleet size for Revised Options 2, 3, and 3A have been reduced by one Tug as a result of using the CTMCF.

Table 3.7-4 presents the cost summary for the revised option definitions. DDT&E costs for the kick stages are not included. Tug costs have been reduced as a result of the cost savings identified in paragraph 3.7.1. Shuttle costs for Options 3 and 3A have been reduced as a result of the reduction in the number of flights required (Table 3.7-3).

3.7.3 Discussion

The following paragraphs present the differences between the final option definitions and revised option definitions. If no differences are indicated, there are none.

3.7.3.1 Option 1 - Cost savings relative to the final option definitions are presented in paragraph 3.6. Costs for Revised Option 1 were determined to be:

	Dollars, Millions			
	DDT&E	Production	Operations	Total
Final Option 1	236.8	166.1	242.2	645.1
Less Kick-Stage DDT&E	-26.1			-26.1
Subtotal	210.7	166.1	242.2	619.0
Cost Savings (para 3.6)	-27.9	-8.5	-17.8	-54.2
Revised Option 1	182.8	157.6	224.4	564.8

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Table 3.7-8 Summary of Revised Option Definitions

	Revised Option 1	Revised Option 2		Revised Option 3			Revised Option 3A		
Development	Direct	Direct		Phased			Phased		
Stages	Single	Single		Single			Stage-and-a-Half		
Configuration	Interim	Delivery	Retrieval	Initial Delivery	Final Delivery	Final Retrieval	Initial Delivery	Final Delivery	Final Retrieval
IOC (Dec)	1979	1983		1980	1983		1980	1983	
Dry Weight	2,886 lb (1,309 kg)	2,750 lb (1,247 kg)	2,982 lb (1,353 kg)	2,804 lb (1,272 kg)	Same as Revised Option 2 Delivery	Same as Revised Option 2 Retrieval	3,874 lb (1,757 kg)	3,820 lb (1,733 kg)	4,043 lb (1,834 kg)
Length	27 ft (8.23 m)	27 ft (8.23 m)		27 ft (8.23 m)			23 ft (7.01 m)		
Propellant Weight	56,700 lb (25,719 kg)	59,800 lb (27,125 kg)		59,800 lb (27,125 kg)			59,800 lb (27,125 kg)		
S/C Capability* Delivery	3,800 lb (1,724 kg)	6,000 lb (2,722 kg)	4,900 lb (2,223 kg)	5,700 lb (2,585 kg)			5,900 lb (2,676 kg)	6,500 lb (2,948 kg)	5,300 lb (2,404 kg)
Retrieval	--	--	1,800 lb (816.5 kg)	--			--	--	1,900 lb (862 kg)
Propulsion	Low P_c OME	Class I		Class I			Same as Revised Option 3		
Avionics	FSI, Current IMU	FSI, Light Weight IMU, Laser Radar for Retrieval		Same as Revised Option 1					
Power	Battery	Solar Array		Solar Array			Solar Array		
Structure	Isolated titanium tanks; titanium, aluminum & composite body structure						Same as Revised Options 1, 2, & 3 plus aluminum drop tanks		
Thermal	Passive paint; MLI each end; base heatshield								

*Spacecraft capability to geostationary orbit.

Table 3.7-3 Programmatic Factors for Revised Option Definitions

	Revised Option 1	Revised Option 2	Revised Option 3	Revised Option 3A
Launch Operations (Years)	11	7	10	10
Crew Size				
ETR CTMCF	69	69	69	69
ETR Launch Site	55	55	55	60
WTR Launch Site	48	55	55	60
Total	172	179	179	189
Number of Flights*				
NASA	119	139	185	180
DOD	108	115	151	151
Total	227	254	336	331
Expendables				
Tugs (Main Stage)	10	6	8	8
Kick Stage 10	3	5	5	5
Kick Stage 1.5	4	—	--	—
Kick Stage 10/1.5	4	--	4	4
Drop Tanks	--	--	--	279
Fleet Size				
Tugs (Main Stage)	15	12	15	15
*Note: Includes reliability losses	3	3	4	4

Table 3.7-4 Cost Summary for Revised Option Definitions

	Costs, $M			
	Revised Option 1	Revised Option 2	Revised Option 3	Revised Option 3A
Tug Costs				
SRT	(12.2)	(19.8)	(19.8)	(20.0)
DDT&E	183	254	263	286
Production	158	153	190	361
Operations	224	208	256	261
Total	565	615	709	908
Number of Flights	227	254	336	331
Average Operations Cost per Flight	0.99	0.82	0.76	0.79
Shuttle Costs	2384	2667	3528	3476
Transportation Cost	2949	3282	4237	4384
( ) Not Included in total				

3.7.3.2 Option 2 - Sensitivity studies indicate that peak funding can be reduced by starting DDT&E one year earlier (Ref 5.8, Vol 2.0, pages 2-162, 2-163, 2-188, and 2-189). This program is recommended for Revised Option 2.

Cost savings relative to the final option definitions are presented in paragraph 3.6. Costs for Revised Option 2 were determined to be:

	Dollars, Millions			
	DDT&E	Production	Operations	Total
Final Option 2	297.7	169.1	233.7	700.5
Less Kick-Stage DDT&E	-18.1			-18.1
Subtotal	279.6	169.1	233.7	682.4
Cost Savings (para 3.6)	-25.1	-16.3	-26.0	-67.4
Revised Option 2	254.5	152.8	207.7	615.0

3.7.3.3 Options 3 and 3A - Paragraph 3.1 presents the effects of not phasing the engine on Final Option 3; paragraph 3.2 presents the effects of delaying the IOC at ETR one year and restricting the number of flights in 1981. Paragraph 3.3 presents the combined effects of these two sensitivity studies on Final Option 3. This program is recommended for Revised Option 3; a similar program is recommended for Revised Option 3A.

Because the Class I engine is used for the Phased Tug-Initial, Tug dry weights and geostationary delivery capabilities are improved as follows:

	Final Option		Revised Option	
	lb	kg	lb	kg
Option 3				
Dry Weight	2,934	1,331	2,804	1,272
Performance Capability	4,400	1,996	5,700	3,585
Option 3A				
Dry Weight	4,004	1,816	3,874	1,757
Performance Capability	4,900	2,223	5,900	2,676

Figures 3.7-1 and 3.7-2 present the Phased Tug-Initial performance capability charts for Revised Options 3 and 3A, respectively.

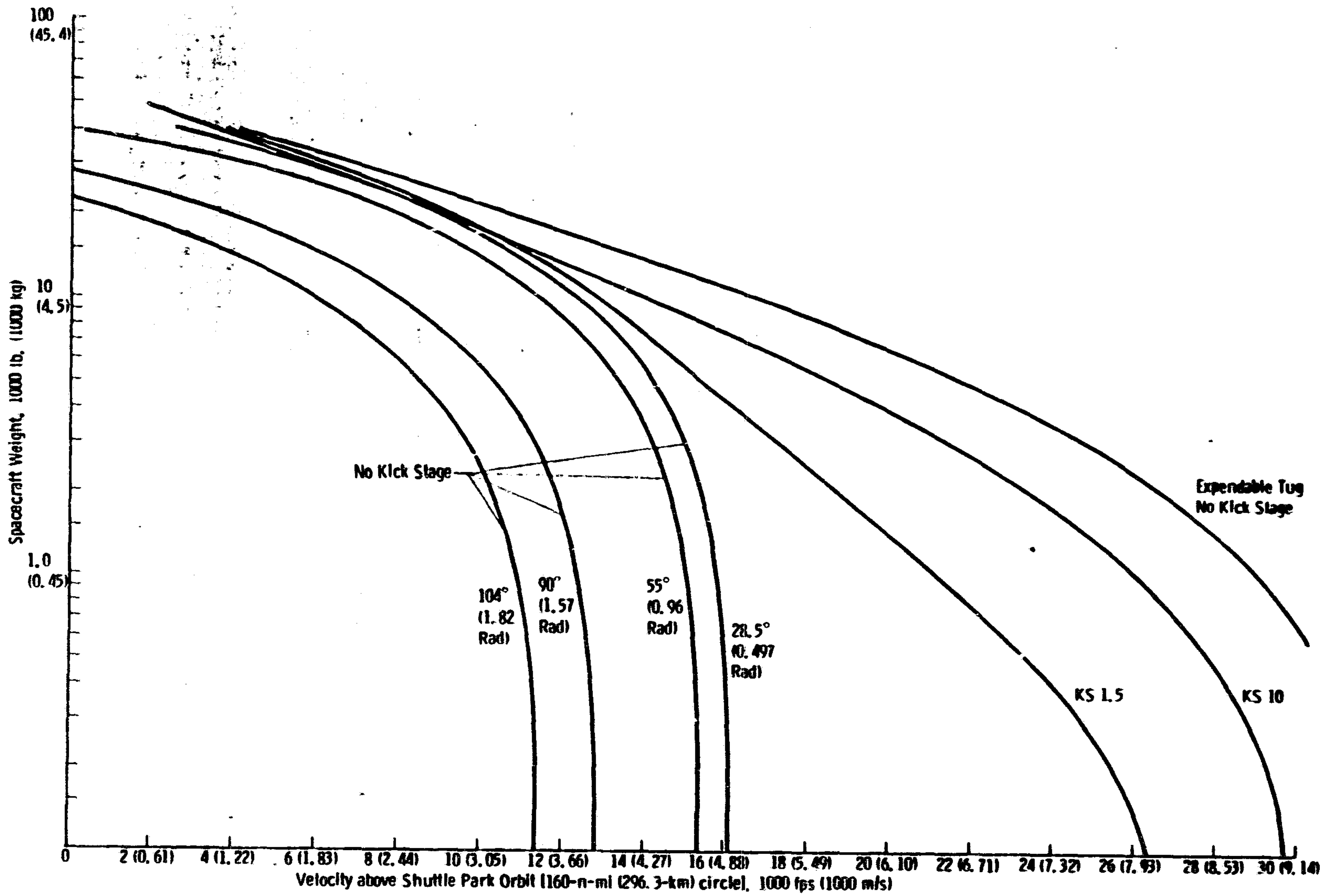

Figure 3.7-1 Revised Option 3 Performance, Phased Tug-Initial with Class I Engine

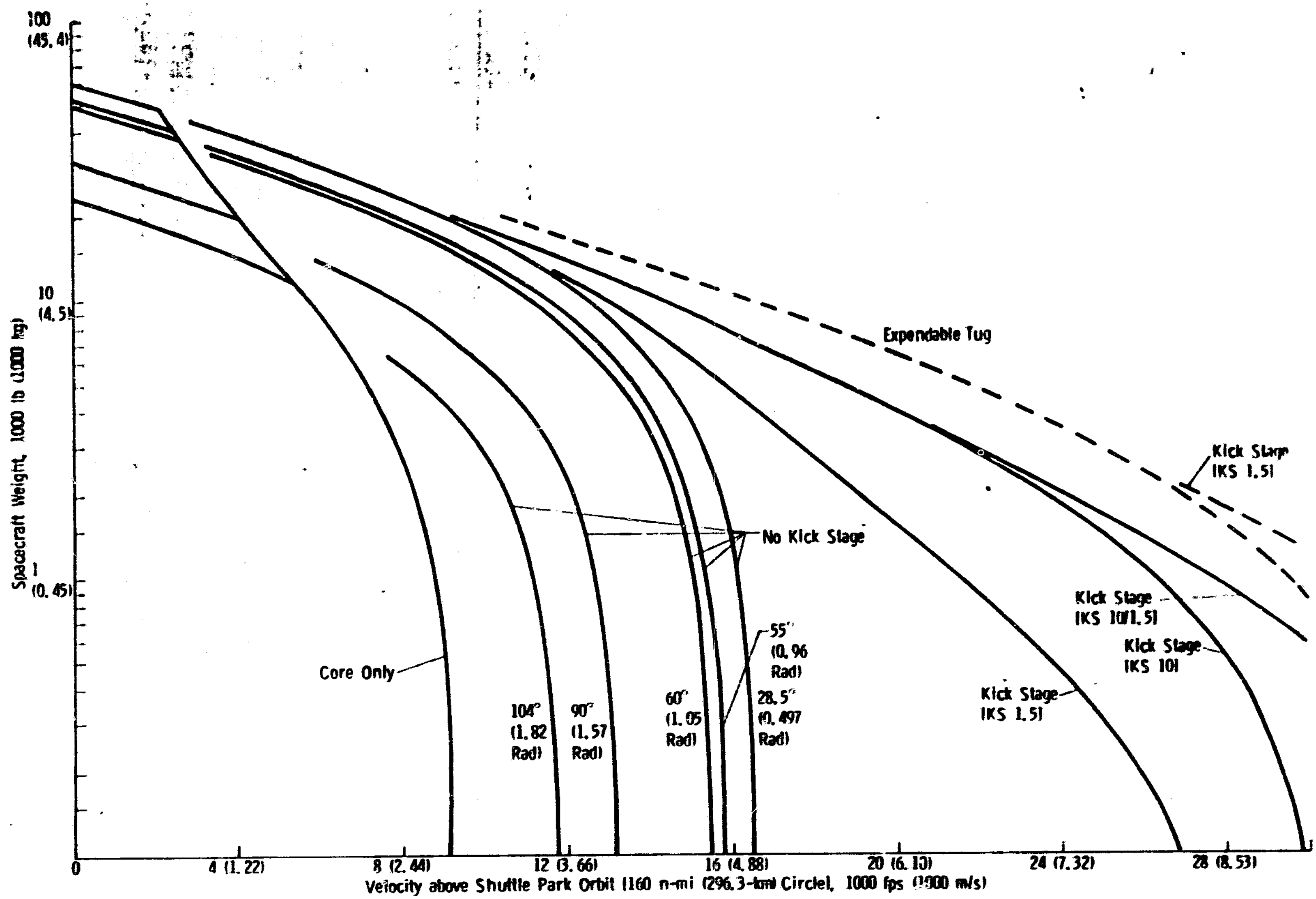

Figure 3.7-2 Revised Options 3A Performance Phased Tug-Initial with Class I Engine

Table 3.7-5 compares the number of flights required for 100% capture, and with programmatics considered. The revised options require fewer flights during the first four years of delivery operations due to the increased performance capability of the Phased Tug-Initial using the Class I engine. Programmatics for the final option definitions limit the number of flights to three in 1980; 100% capture is achieved in 1981. Programmatics for the revised options eliminate the three flights in 1980, due to the delayed IOC, and limits the flights in 1981 rather than drive the program to 100% capture; 100% capture is achieved in 1982.

Table 3.7-6 compares the mission accomplishment in terms of the spacecraft delivered and retrieved. Programmatics considerations limit the number of spacecraft delivered in 1980 for the final options. None are delivered in 1980 for the revised option and the number of spacecraft delivered in 1981 is limited; 100% capture is achieved for retrieval in both cases.

Cost savings relative to the final option definitions are presented in paragraph 3.6. Costs for Revised Option 3 were determined to be:

	Dollars, Millions			
	DDT&E	Production	Operations	Total
Final Option 3	353.7	209.3	318.3	881.3
Less Kick-Stage DDT&E	-26.1			-26.1
Subtotal	327.6	209.3	318.3	885.2
Cost Savings (para 3.6)	-64.6	-18.7	-62.5	-145.8
Revised Option 3	263.0	190.6	255.8	709.4

Costs for Revised Option 3A were determined as follows:

	Dollars, Millions			
	DDT&E	Production	Operations	Total
Final Option 3A	380.6	388.2	326.8	1095.6
Less Kick-Stage DDT&E	-26.1			-26.1
Subtotal	354.5	388.2	326.8	1069.5
Cost Savings (para 3.6)	-68.9	-26.9	-66.2	-162.0
Revised Option 3A	285.6	361.3	260.6	907.5

Table 3.7-5 Flight Requirements for Options 3 and 3A

	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	Total
OPTION 3												
100% Capture												
Final Option	21	17	19	29	43	37	41	39	36	41	43	366
Revised Option	20	14	17	26	43	37	41	39	36	41	43	357
Programmatics												
Final Option	3	17	20*	29	43	38*	41	40*	36	41	44*	352
Revised Option	0	9	17	27*	43	38*	41	40*	36	41	44*	336
OPTION 3A												
100% Capture												
Final Option	20	15	18	27	43	37	41	39	35	39	43	357
Revised Option	19	14	16	25	43	37	41	39	35	39	43	351
Programmatics												
Final Option	3	15	19*	27	43	38*	41	40*	35	39	44*	344
Revised Option	0	9	16	26*	43	38*	41	40*	35	39	44*	331

*Includes one reliability loss

Table 3.7-6 Mission Accomplishment for Options 3 and 3A

	100% Capture	Programmatic Capture	
		Final Option	Revised Option
Spacecraft Delivered			
NASA	201	189	181
DOD	186	167	162
Total	387	356	343
Spacecraft Retrieved			
NASA	87	87	87
DOD	84	84	84
Total	171	171	171
Total Spacecraft	558	527	514

3.7.4 Recommendations

Final option definitions presented in the *Selected Option Data Dump* (Ref 5.8) have been revised to incorporate the results of sensitivity studies and additional analysis. These revisions are referred to as revised option definitions and represent our recommendation for the best Space Tug (Storable) for each appropriate programmatic option.

3.8 Assessment of DOD Programmatics

3.8.1 Introduction

The *Selected Option Data Dump* (Ref 5.8) included schedule and cost data based on DOD programmatics; however, in accordance with previous agreements, no attempt was made to assess the pros and cons of DOD programmatics relative to NASA programmatics. The purpose of this study was to provide a qualitative assessment of DOD programmatics. Study details are presented in Martin Marietta letter 73Y-81,183, dated October 19, 1973, Contract NAS8-29675, Assessment of DOD Programmatics.

3.8.2 Summary of Results

The DOD programmatic approach reduces the risk of modifications during production and operations because an operational test and evaluation (OT&E) is conducted before commitment to fullscale production. However, this delays production and produces an uneven distribution in yearly funded requirements, which is considered undesirable.

Because the Tug fleet is relatively small (approximately 15) and centrally located, modifications can be readily incorporated after delivery.

3.8.3 Recommendation

It is recommended that commit-to-production not be constrained by flight-test evaluation. Evaluations and reviews can be held in a timely fashion so that the start of production is not delayed.

3.9 Validation Phase for Space Tug (Storable)

3.9.1 Introduction

The purpose of this section is to identify recommended tasks for the Air Force validation Phase of the Storable Space Tug Program. The tasks are identified in terms of specific outputs that must be backed up by preliminary design, analyses, and trade studies. The section is in general agreement with and in an expansion of the outputs identified in AFSCP 800-3.

It is assumed that supporting research and technology (SRT) tasks in the Appendix to Vol 5.0, *Selected Option Data Dump* (Ref 5.8) are conducted in parallel with or as part of the validation phase. The SRT tasks identified include the prototype testing necessary to define hardware characteristics and eliminate technology risks.

Principal outputs of the validation phase are the Part I configuration item (CI) detailed performance specification and interface requirements specifications. Criteria and requirements documents and detailed plans are provided to validate schedules and costs for the full-scale development and production phases.

Outputs identified in the following paragraphs define requirements for the allocated baseline, which provides a firm foundation for commitment to full-scale development.

3.9.2 Validation-Phase Task Identification

The following tasks are listed for the DOD validation phase.

3.9.2.1 Research and Technology (including hardware prototype testing) - This work is performed in parallel with or as part of the validation phase details presented in the supporting research and technology (SRT) appendix to Vol 5.0 of the *Selected Option Data Dump* (Ref 5.8).

3.9.2.2 Specification (MIL-STD-490)

1) Updated system specification

2) Part I, configuration item (CI) detailed performance specifications for:

   (a) Prime equipment

   (b) Real property facility items

   (c) Noncomplex items

(d) Computer programs

(e) Critical identifiable engineering components

3) Preliminary interface requirements specifications, ICDs (referenced in above specifications) for:

(a) Tug to spacecraft

(b) Tug to Orbiter

(c) Tug Engine to Tug

4) Procurement specifications for long-lead items.

3.9.2.3 Criteria and Requirements Documents

1) Design criteria

2) Test and checkout criteria

3) Operational software requirements

4) GSE requirements (including software)

5) Facility requirements

6) Software validation requirements

7) Tooling requirements and tool specification orders

8) Human factors criteria

9) Inventory equipment requirements

3.9.2.4 Plans

1) contractor full-scale development plan, including configuration management plans, cost, and schedule control plan.

2) Test plans

(a) Integrated systems test plan

(b) Full-scale development test plan, including component and subsystem development, qualification, acceptance, and flight-test evaluation

(c) Additional CI prototype testing before full-scale development

3) Training requirements plan

4) Logistics plan

5) Make-or-buy plan

6) Design standardization program plan

7) Manufacturing plan

8) Advance process plan

9) Mission success plan, including reliability assessment, quality assurance, maintainability, and failure reporting and tracking.

10) Tug refurbishment plan

11) Flight operations plan, including ground support

12) Tug/Shuttle/payload management integration plan

13) Safety plan

14) Subcontractor management plan

15) EMC plan

16) Communications plan

17) Value engineering plan

18) Transportation plan

19) Plan for operational procedures

3.9.2.5 Schedules

1) Full-scale development phase at the CI level

2) Planning schedules for the production phase at the CI level

3) Schedule commitments for subcontracted items

4) Integrated schedules for Shuttle/Tug operations

3.9.2.6 Costs

1) Estimates at the CI level for a cost-type proposal for the full-scale development phase

2) Planning cost estimates at the CI level for the production phase

3) Cost estimates for major procurement items based on vendor quotations

3.9.2.7 Study Results

1) System and subsystem trade studies, including cost and schedule

2) Risk assessment, including assessment of supporting research and technology status

3) Performance and targeting analyses

4) Mission capability analyses

3.10 Candidate 1974 Study Tasks for the High-Technology Space Tug

3.10.1 Introduction

This section identifies specific tasks that NASA should pursue in CY 1974 to evolve a High-Technology Space Tug (HTST) in the 1985 time frame to supplement or replace the interim Orbit-to-Orbit Shuttle (OOS) for the Space Transportation System (STS).

3.10.2 Summary

NASA should make maximum use of Space Tug System Study results, recognizing the interim OOS in the STS. Results of these studies should be maintained, combined, and modified to provide a cost-effective plan to integrate the HTST into the STS in the 1985 time period. Emphasis should be placed on continuation of mission modeling, identification of performance and programmatic requirements, detailed advanced design studies in certain areas, investigation of the entire spectrum of upper stages, mission and ground operations studies, and resolution of safety issues.

3.10.3 Discussion

A brief description of each task follows.

3.10.3.1 Systems Analysis - The objective of the systems analysis tasks is to seek and define the most cost-effective program for integrating the HTST into the STS. Specific tasks are discussed below.

a. Mission Model Assessment - During 1973, we evaluated more than 40 mission models that were deterministic; i.e., the launch and retrieval data for a given spacecraft were specified. It is anticipated that such mission models will continue to evolve. These should be evaluated using typical HTST candidates, recognizing the existence of the interim OOS. Missions from which the HTST is more cost effective should be identified.

Mission models should also be examined, using a probabilistic approach in which the launch date for a given spacecraft or satellite network is uncertain. Such modeling would take into account variations in satellite replacement due to random failures, infant mortality, and wear-out. This would in turn affect Tug fleet size and provide additional visibility to the variability of launch rate, fleet size, and cost.

b. Cost-Effective HTST Programs - Tug/spacecraft combinations should be examined in light of known Shuttle size and weight limitations to determine the most cost-effective method of satisfying mission model requirements. Interim OOS and HTST candidates should be evaluated and compared. Spacecraft mission requirements for the HTST should be identified as a result of

time phasing, performance capability, and costs relative to the interim OOS. Kick-stage candidates evolving from the task described in paragraph 3.3.2 should be included.

c. *Accumulate Cost Data and Evaluate Uncertainties* - Cost data resulting from the Space Tug Systems Studies should be accumulated, documented, and compared. Discrepancies and uncertain areas should be investigated to obtain better cost data. Results of probabilities mission modeling will also indicate variations in operational costs for which probability distributions can be derived.

d. *Trade-Off Requirements versus Cost and Performance* - During the Space Tug Systems Studies, certain requirements, ground rules, and assumptions drove the resulting design and programmatic options. Trade-off studies should be conducted to optimize the requirements, performance, design, cost, and programmatics, which would lead toward identification and definition of the most cost-effective program.

e. *Servicing Mission Requirements* - During the Space Tug Systems Study, some attention was given to a servicing mission. It should be further explored in 1974 to determine and evaluate specific requirements for rendezvous and docking, flight operations, and spacecraft-to-Tug interface requirements. Design and operational studies should be conducted to better understand the operations and requirements of the Service Module (SM) and Service Replacement Unit (SRU).

f. *Economic Studies of Spacecraft Retrieval and Servicing* - The interim OOS provides for spacecraft delivery but cannot retrieve a disabled or spent spacecraft. The high-technology Space Tug will have retrieval as well as delivery capability; however, the economics of retrieval are controversial. Another alternative is to provide spacecraft servicing on orbit.

The economics of selective spacecraft retrieval or servicing should be investigated to determine which spacecraft should be retrieved or serviced. Trade-offs should be based on costs for spacecraft, refurbishment, and transportation. It is anticipated that the more expensive spacecraft justify retrieval, whereas heavier spacecraft would justify servicing.

g. *Program Plan* - A program plan should be developed that leads to initiation of the development phase and thence to production and operation. Advanced studies, conceptual design, and supporting research and technology (SRT) tasks should be identified and scheduled. Major program milestones and decision points should be defined. The program plan would provide the basis for NASA's pursuit of the HTST and monetary expenditures.

h. Maintain Criteria and Spacecraft Definition - The Space Tug Systems Studies were based on certain criteria and spacecraft definitions. Other criteria, ground rules, assumptions, and interpretations evolved during the studies. These criteria should be maintained, updated, and expanded. Discrepancies and different interpretations should be resolved and results documented. The results will provide the basis for the system performance specification (para i.) and the ultimate design specifications for the HTST.

i. Preliminary Performance Specification - A preliminary performance specification should be started in 1973, maintained, and updated in subsequent years. The specification should define overall performance requirements for the HTST system and programmatic constraints. This would provide the basis for conceptual studies, program definition and, ultimately, the basis for competitive contractor bidding.

3.10.3.2 Upper-Stage Evaluation

a. Background - All Tugs thus far defined have required kick stages of various energy requirements. Kick-stage requirements vary from those needed only for high-delta-velocity planetary missions for high-technology Tugs, to those needed for 50% of geostationary placement missions for the reusable OOS. The kick stages vary in size as a function of mission requirements and Tug capability. Simple state-of-the-art solid-rocket-motor kick stages have generally been satisfactory for geostationary placement with the OOS, and to a lesser extent for planetary missions.

Higher-energy kick stages have been considered for many planetary applications. These include low-thrust, very-high I_{sp} ion-propulsion stages powered by solar-electric or nuclear-electric systems. These higher-energy kick stages have also been considered for possible geostationary applications such as spacecraft retrieval and on-orbit spacecraft service.

Between the high-energy kick stages and the state-of-the-art solid-rocket-motor kick stages lie flourine-based liquid-propellant stages, higher-performance, efficiently packaged solid-rocket-motor kick stages, liquid-propellant kick stages derived from Transtage hardware, and kick stages based on planetary-orbit-inject propulsion systems.

b. Study Approach - The entire matrix of kick-stage possibilities should be assessed for application to the various Tug configurations currently under consideration. Cost, performance, and mission capture evaluation and trade-offs should be conducted to establish Tug-to-kick-stage "best fit" and cost effectiveness. The logical transition of a select kick stage from interim OOS to

a high-technology Tug is an obvious goal. In particular, a kick stage based on Transtage components should be sized for optimum fit for reusable OOS geostationary delivery and for later application to high-technology Tug planetary delivery.

High-energy kick stages should be evaluated for multiple application with interim and high-technology Tugs, with emphasis on use with OOS to capture the NASA planetary segment of the mission model.

c. *Sequence* - Kick-stage assessment should follow the sequence:

1) Mission requirement assessment of various user's desires and available mission models (to be worked in conjunction with the previous task);

2) Mission requirement assessment as a function of Tug delivery capability;

3) Stage sizing;

4) Mission capture of various Tug/kick-stage combinations;

5) Cost assessment and economic effects of various Tug/kick-stage combinations;

6) Selection of optimum kick-stage configurations.

3.10.3.3 Advanced Design

a. *Structures*

1) Propellant Slosh Analysis - Satisfactory methods and computer analyses of propellant behavior in slanted or asymmetric tanks should be developed. This includes the interaction of fluid with thin-walled tanks as it pertains to structural loads and control-system stability.

2) Lightweight Structure (Composites) for Nontank Structure - Additional studies of the application of composites to minimize nontank or skirt structural weight should be conducted. This would use the loads and configuration applicable to concepts as defined in the Space Tug Systems Studies and would be in addition to the work now being done under contract NAS8-29979, "Design Fabrication and Test of Lightweight Shell Structure."

3) Docking Mechanisms

- Generate a more detailed preliminary design of the docking mechanism concept resulting from the Space Tug Systems Studies.

- Perform preliminary dynamic analysis of this preliminary design.

- Begin work to develop analytical tools for docking and capture of an elastic spinning satellite.

b. *Propulsion*

1) Propellant Dump Philosophy and System Safing - The execution of "in-space" dumping of storable propellants and provision of a safe and passive propulsion system after a mission or mission abort has been recognized as a prime area of concern. A study should be undertaken to establish the propellant dump philosophy and system safing technique.

2) Evaluation of Propellant Utilization Systems - Controlling propellant residuals is considered a critical problem in minimizing weight penalties for the Space Tug main propulsion system. To minimize propellant residuals, an accurate and reliable propellant utilization (PU) system must be used that includes a propellant quantity gaging system and necessary control electronics and mechanisms. The objective is to evaluate and select the preferred PU system and establish its performance.

c. *Avionics*

1) Flight Test Feasibility Studies - A study should be made to investigate the feasibility of an avionics subsystem and components test philosophy based on "piggyback" on the interim OOS. That is, the interim OOS will provide the perfect test bed for qualification and testing of data management, power, and especially navigation equipment (one-way Doppler, interfermeter landmark tracker, horizon sensors, scanner laser radars, etc) of new design intended for the mid 1980s. If the test concept appears feasible, a plan should be roughed out and the program impact assessed.

2) Fault Isolation and Replacement Philosophies - A comparison of fault isolation and replacement philosophies should be conducted. This should include redundancy planning philosophy, data management pilot-copilot or majority-vote and software routines. This study cannot be performed without a cursory analysis, replete with assumptions as to the caution and warning philosophies of the Orbiter.

3) On-Board Checkout - An investigation should be made to determine the cost savings and technical advantages of system checkout through the use of the flexible signal interface data-management approach. The approach must be deepened somewhat to include the assumption of black-box characteristics, then a vendor control technique can be developed and expanded to provide the cost savings data.

4) Rendezvous and Docking - Blind rendezvous and docking should be investigated by:

   - Developing the guidance algorithms;

   - Investigating the applicability of our Mars landing-site-selection hardware (image dissector) and accompanying software (edge detection Sun/shadow) to blind dock to a cooperative vehicle.

   An emperial study should be made of man-in-the-loop rendezvous and docking using the Martin Marietta space operations simulation laboratory, studying the effects of:

   - Delay in picture, range data;

   - Degradation in the reconstructed picture;

   - Minimum time-line maneuvers.

   This effort can be done for two manmonths of effort if the laboratory is up and running for other purposes. This was the case in 1973 and may be in 1974.

5) Communications - Investigate in-depth Orbiter communications interface with the Tug vehicle--recommend optimum frequency allocation or compatible Orbiter, Tug, spacecraft, relay satellite and ground network RF links.

6) Solar Array or Fuel Cells - A study should be made of solar arrays versus fuel cells for the HTST. This study should relate the development of these technologies to selection of the interim OOS and to the heavy impact on cost and development.

7) Solar-Array Deployment - A study should be conducted to define problems associated with deployable equipment like solar arrays and antennas. The study should include life time cycling, ACS impingement, emergency action on failure before Orbiter/Tug retrieval, contamination, Sun-shadow effect, and interference.

d. Interfaces - Additional studies should be conducted to ensure that HTST and OOS interfaces with the Orbiter are compatible in a manner that requires minimum Shuttle modification when transitioning from the OOS to the HTST. Items requiring additional study are:

1) A satisfactory method of achieving proper alignment and placement of the Tug in the Cradle;

2) A suitable method of latching and unlatching the Tug retention devices on the Cradle;

3) Number of Tug-to-Cradle interface points to obtain minimum weight;

4) A method of making remote connections of the Cradle-to-Tug umbilicals;

5) Location and method of support for Cradle-to-Orbiter dump lines and electrical umbilicals;

6) Review and comparison of OOS structural, mechanical, electrical and functional requirements. Recommend OOS/Orbiter interface compromises to accept HTST with minimum modification and/or HTST compromises to be compatible with OOS/Orbiter interfaces.

7) Study the effects of converting from an interim storable OOS to a cryogenic HTST.

3.10.3.4 Mission Operations - Systems operability studies should be continued concurrently with systems analyses and advanced design studies. The ground and in-flight checkout philosophy should be established and crew involvement defined. Constraints or operational limitations should be identified, documented, and maintained.

3.10.3.5 Ground Operations - The functional flow, test requirements, checkout philosophy, GSE and facility requirements evolving from the systems studies should be maintained and up-dated. Differences between the studies should be compared and resolved. Cleanliness requirements, propellant handling and Tug refurbishment, handling, and installation in the Orbiter should be studied, trade-offs conducted, and preliminary requirements defined. Considerations should be given to integration with interim OOS activities, and Orbiter and spacecraft integration.

3.10.3.6 Safety

a. Trade-off and sensitivity studies should be conducted to determine the effects of safety requirements on vehicle design, performance, and cost. For example, safety criteria used for the Space Tug Systems Study are more conservative than those for OOS.

b. Additional studies should be conducted to:

1) Identify propellant fire hazards and preventive action;

2) Explore the possibility of propellants freezing in lines;

3) Explore the possibility or degree of Orbiter contamination and preventive action;

4) Resolve safety issues of hypergolic and cryogenic propellants.

4.0 CONCLUSIONS AND RECOMMENDATIONS

4.1 FINAL OPTION DEFINITIONS AND SENSITIVITY STUDIES

We have addressed the study objectives and key issues in a logical and systemmatic manner, and have defined the final options and associated programmatics and cost in depth. A supporting research and technology (SRT) program has been identified to minimize program risk. Sensitivity studies and additional analyses have provided additional insight. The significant results and conclusions are summarized as follows:

- 100% mission capture (about 500 spacecraft) can be achieved with a small (approximately 15) Tug fleet.
- A few (approximately 10) Tugs and kick stages must be expended to capture the very high-energy planetary missions.
- Any spacecraft delivered can be retrieved using a delayed retrieval flight mode.
- Multiple spacecraft delivery minimizes the number of Shuttle flights required.
- Tug length is as important as delivery capability in minimizing the number of Shuttle flights.
- The storable Tug can readily accomplish a 30-day servicing mission.
- Spacecraft retrieval is relatively inexpensive to develop, but expensive to routinely implement.
- The Tug main stage should consist of a single stage.
- A high level of safety and reliability can be achieved; safety and reliability are equal drivers.
- Storable propellants provide maximum safety due to their stability and precise reaction predictability; tank venting is not required after loading. Storable propellants have been used for more than ten years without a disabling injury or major incident.
- Storable Tugs offer efficient use of payload-bay volume, simple interfaces with Orbiter and ground systems, safe operating modes, and simple design leading to low DDT&E costs.

- Use of separation and docking modules significantly increases the flexibility of the Tug and is cost effective.

- Autonomy levels do not significantly affect Tug performance and cost.

- The final option definitions advance the state of the art with minimum development costs.

- The reusability of the selected storable Tug configurations provide minimum production and operating costs.

- The final option definitions provide minimum risk of achieving performance goals within the estimated costs and schedules.

- Considerable cost savings can be achieved by revising the ground rules and assumptions used or evolved during the study.

- Extending the DDT&E phase reduces peak funding, but slightly increases total cost.

- The main engine should not be phase-developed.

- Commit-to-production should not be contingent on flight-test evaluation (DOD programmatics).

4.2 REVISED OPTION DEFINITIONS

Final option definitions and associated programmatics and costs were presented in the *Selected Option Data Dump* (Ref 5.8) in September 1973. Some of the above conclusions indicate that the final option definitions should be revised, specifically:

- Delete life test article and thermal-effects test article;

- Assume no cradle attrition;

- Load propellant on pad (but out of Orbiter);

- Use central tug maintenance and checkout facility (CTMCF);

- Use existing facilities; delete Class 100,000 cleanliness requirement;

- Assume control center equipment and maintenance is provided as GFP (use existing equipment);

- Assume control center crew is provided by the government and is not charged to Tug;

- Perform acceptance testing in CTMCF;
- Train NASA and DOD crews jointly;
- Do not include kick-stage DDT&E costs in Tug costs;
- Start DDT&E phase one year earlier for Option 2;
- Do not phase the engine (Options 3 and 3A); delay initial IOC one year; do not drive the program to 100% capture in 1981.

Accordingly, this section presents the recommended "revised option definitions" that incorporate the above revised ground rules and assumptions.

Table 4-1 presents the requirements for the revised option definitions; the lower section summarizes the differences between the requirements for the final option definitions and the revised option definitions. The cost savings items result from the above revisions to certain ground rules and assumptions used or evolved during the study. Because all Tug candidates (interim, cryogenic, or storable) require kick stages, which are not well defined, DDT&E costs for kick stages are not included in the total costs. DDT&E is started one year earlier in Option 2 to reduce annual peak funding requirements. The engine is not phased in Options 3 and 3A, and the IOC for the Phased Tug-Initial at ETR is delayed one year; a build-up in flight rate and crew size is also provided at WTR and ETR rather than drive the program directly to 100% capture in 1981. Table 4-2 presents a summary description of the revised option definitions, including physical characteristics, performance capabilities, and identification of major subsystems.

Table 4-3 presents the mission accomplishment for the revised option definitions, including programmatic considerations. The flight rate is limited in the first two years of operations and reliability losses are included. Table 4-4 compares the number of flights used for programmatics with the number of flights required for 100% capture.

Table 4-5 presents the significant programmatic data for the Revised Options. Crew sizes during the first two years of operations are smaller than those shown, due to the build-up in flight rate. Except for Option 1, use of a centralized tug maintenance and checkout facility (CTMCF) reduces crew size and Tug fleet size. The length of the operational program and crew size drive the operational costs. Fleet size affects production costs and is primarily driven by the number of expendables and reliability losses. Note that a large number of flights is accomplished with a small Tug fleet, due to the reusability of the Space Tug (Storable).

Table 4-1. Requirements for Revised Option Definitions

	Revised Option 1	Revised Option 2	Revised Option 3	Revised Option 3A
IOC	1979	1983	1980/1983	1980/1983
Payload Requirement Delivery Retrieval	3500 lb (1588 kg) ----	3500 lb (1588 kg) 3500 lb (1588 kg)	3500 lb (1588 kg) 2200 lb (998 kg)	3500 lb (1588 kg) 2200 lb (998 kg)
Vehicle	Single Stage	Single Stage	Single Stage	Stage-and-a-half
Additional Requirements	Delivery-only Low DDT&E dollars No growth 36-hr max duration	Direct-developed Delivery & retrieval in 1983	Phase-developed Delivery-only 1980-1983 Retrieval and Increased Performance in 1983	Phase-developed Delivery-only 1980-1983 Retrieval and Increased Performance in 1983
Revisions to Final Option Definitions	Cost savings items incorporated No DDT&E costs for kick stages	Cost savings items incorporated No DDT&E costs for kick stages Start DDT&E one year earlier	Cost savings items incorporated No DDT&E costs for kick stages Engine not phased ETR IOC delayed one year Flights restricted in 1981	Cost savings items incorporated No DDT&D costs for kick stages Engine not phased ETR IOC delayed one year Flights restricted in 1981

Table 4-2 *Summary of Revised Option Definitions*

	Revised Option 1	Revised Option 2		Revised Option 3			Revised Option 3A		
Development	Direct	Direct		Phased			Phased		
Stages	Single	Single		Single			Stage-and-a-Half		
Configuration	Interim	Delivery	Retrieval	Initial Delivery	Final Delivery	Final Retrieval	Initial Delivery	Final Delivery	Final Retrieval
IOC (Dec)	1979	1983		1980	1983		1980	1983	
Dry Weight	2,886 lb (1309 kg)	2,750 lb (1247 kg)	2,982 lb (1353 kg)	2,804 lb (1272 kg)	Same as Revised Option 2 Delivery	Same as Revised Option 2 Retrieved	3,874 lb (1757 kg)	3,820 lb (1733 kg)	4,043 lb (1834 kg)
Length	27 ft (8.23 m)	27 ft (8.23 m)		27 ft (8.23 m)			23 ft (7.01 m)		
Propellant Weight	56,700 lb (25,719 kg)	59,800 lb (27,125 kg)		59,800 lb (27,125 kg)			59,800 lb (27,125 kg)		
Spacecraft Capability*									
Delivery	3,800 lb (1724 kg)	6,000 lb (2722 kg)	4,900 lb (2223 kg)	5,700 lb (1996 kg)			5,900 lb (2676 kg)	6,500 lb (2948 kg)	5,300 lb (2404 kg)
Retrieval	----	----	1,800 lb (816.5 kg)	----			----	----	1,900 lb (862 kg)
Propulsion	Low P_c OME	Class I		Class I			Same as Revised Option 3		
Avionics	FSI, Current IMU	FSI, Lightweight IMU, Laser Radar for Retrieval		Same as Revised Option 1					
Power	Battery	Solar Array			Solar Array		Solar Array		
Structure	Isolated Titanium Tanks; Titanium, Aluminum, and Composite Body Structure						Same as Revised Options 1, 2, & 3 plus Aluminum Drop Tanks		
Thermal	Passive Paint; MLI each End; Base Heat Shield								

*Spacecraft capability to geostationary orbit

Table 4-3 Summary of Mission Accomplishment with Programmatic Considerations - Revised Options*

	Revised Option 1	Revised Option 2	Revised Option 3	Revised Option 3A
Spacecraft Delivered				
NASA	189	.110	181	181
DOD	149	111	162	162
Total	338	221	343	343
Spacecraft Retrieved				
NASA	---	79	87	87
DOD	4†	79	84	84
Total	4†	158	171	171
Total Spacecraft	342	379	514	514
Delivery Flights				
NASA	119	59	97	93
DOD	108	34	65	65
Total	223	93	162	158
Retrieval Flights				
NASA	---	80	88	87
DOD	4†	81	86	86
Total	4†	161	174	173
Total Flights	227	254	336	331

*Total mission model reduced for Shuttle limitations and build-up rate. Flights are increased for reliability losses.

†Sortie

Table 4-4 *Comparison of Flights Used for Programmatics with Flights Required for 100% Capture - Revised Options*

	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	Total
Revised Option 1												
Programmatics	3	14	18*	29	25	23*	21	27	20*	26	21	227
100% Capture	17	14	17	29	25	22	21	27	19	26	21	238
Revised Option 2												
Programmatics					15	31	42*	41	37*	42	46*	254
100% Capture					45	43	41	41	36	42	45	293
Revised Option 3												
Programmatics	0	9	17	27*	43	38*	41	40*	36	41	44*	336
100% Capture	20	14	17	26	43	37	41	39	36	41	43	357
Revised Option 3A												
Programmatics	0	9	16	26*	43	38*	41	40*	35	39	44*	331
100% Capture	19	14	16	25	43	37	41	39	35	39	43	351

*Note: Includes one reliability loss

Table 4-6 Programmatic Factors for Revised Options

	Revised Option 1	Revised Option 2	Revised Option 3	Revised Option 3A
Launch Operations (Years)	11	7	10	10
Crew Size - ETR CTMCF	69	69	69	69
- ETR Launch Site	55	55	55	60
- WTR Launch Site	48	55	55	60
- Total	172	179	179	189
Number of Flights* - NASA	119	139	185	180
- DOD	108	115	151	151
- Total	227	254	336	331
Expendables - Tugs (Main Stage)	10	6	8	8
- Kick Stage 10	3	5	5	5
- Kick Stage 1.5	4	-	-	-
- Kick Stage 10/1.5	4	-	4	4
- Drop Tanks	-	-	-	279
Fleet Size - Tugs (Main Stage)	15	12	15	15
*Note: Includes Reliability Losses	3	3	4	4

Table 4-6 summarizes the total costs for the Revised Options. DDT&E costs for the kick stages are not included. The cost of supporting research and technology (SRT) is shown, but not included in the totals. The cost per flight is based on operating cost and does not include the cost of expendables. Shuttle costs are based on $10,500,000 per flight. Tug costs for Revised Option 2 are greater than for Revised Option 1, due to the greater complexity in DDT&E. Production cost per unit is higher, however, fleet size is smaller. The span time for Revised Option 2 is shorter, which tends to reduce operations costs. Tug costs for Revised Option 3 are higher than for Revised Option 2, due to the phased development, larger fleet size, and longer operational program. Because Revised Option 3 has significantly more flights, the cost per flight is less. Tug costs for Revised Option 3A are greater than for Revised Option 3, due to added development and production costs of the drop tanks, which are expended. Because the number of flights is only slightly reduced, the cost per flight is higher. Transportation costs are driven by Shuttle costs, which are in turn driven by the number of flights. Revised Option 3A is an exception because Tug costs are significantly greater than for Revised Option 3; however, the number of flights is only slightly reduced.

4.3 SUGGESTED ADDITIONAL EFFORT

During the Space Tug Systems Study, it was decided that the Department of Defense would provide an interim Tug, referred to as the Orbit-to-Orbit Shuttle (OOS), while NASA would pursue the long range Tug referred to as the High Technology Space Tug (HTST).

NASA should make maximum use of the Space Tug System Study results, recognizing the interim OOS in the Space Transportation System (STS). Results of these studies should be maintained, combined, and modified so as to provide a cost-effective plan to integrate the HTST into the STS in the 1985 time period. Emphasis should be placed on continuation of the mission modeling, identification of performance and programmatic requirements, detailed advanced design studies in certain areas, investigation of the entire spectrum of upper stages, continuation of mission and ground operations studies, and resolution of safety issues.

Table 4-6 Cost Summary for Revised Option Definitions

	Costs, $M			
	Revised Option 1	Revised Option 2	Revised Option 3	Revised Option 3A
Tug Costs				
SRT	($ 12.4)	($ 16.6)	($ 16.6)	($ 16.6)
DDT&E	182	249	266	289
Production	162	155	194	364
Operations	233	213	263	268
Total	$ 577	$ 617	$ 723	$ 921
Number of Flights	227	254	336	331
Average Operations Cost per Flight	$ 1.03	$ 0.84	$ 0.78	$ 0.81
Shuttle Costs	$2,384	$2,667	$3,528	$3,476
Transportation Cost	$2,961	$3,284	$4,251	$4,397

The following list summarizes specific tasks that should be started in CY 1974 by NASA and its contractors.

a. *Systems Analyses*

- Assess deterministic and probabilistic mission models
- Identify cost-effective HTST programs
- Accumulate cost data and evaluate uncertainties
- Trade off requirements versus cost and performance
- Study servicing mission requirements
- Conduct economic studies of spacecraft retrieval and servicing
- Develop a program plan
- Maintain criteria and spacecraft definitions
- Develop a preliminary performance specification.

b. *Upper (Kick) Stage Evaluation*

- Evaluate the entire spectrum of kick-stage possibilities for common application to the interim OOS and HTST
- Evaluate a kick-stage derived from Transtage components.

c. *Advanced Design*

1) Structures

  - Develop propellant slosh analyses
  - Conduct additional studies of composites
  - Generate preliminary design of docking mechanisms and perform preliminary dynamic analyses.

2) Propulsion

- Establish propellant philosophy
- Evaluate propellant utilization systems.

3) Avionics

- Study feasibility of OOS flight test
- Establish fault isolation and replacement philosophies
- Investigate on-board checkout
- Conduct rendezvous and docking studies
- Investigate communications interfaces
- Trade off solar array versus fuel cells
- Study solar-array deployment.

4) Interfaces

- Compare OOS interfaces with HTST
- Identify OOS, HTST, and Shuttle compromises to achieve compatibility
- Determine the effects of transitioning from an OOS of one propellant to an HTST of another propellant.

d. Mission Operations

- Establish checkout philosophy
- Define crew participation
- Identify operational constraints.

f. Ground Operations

- Maintain and update previous studies
- Resolve differences
- Conduct trade-off studies
- Integrate HTST operations with OOS.

g. Safety

- Trade off safety requirements with performance and cost
- Revolve safety issues.

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